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REAL-AIR DATA-REDUCTION PROCEDURES BASED ON FLOW PARAMETERS MEASURED IN THE TEST SECTION OF SUPERSONIC AND HYPERSONIC FACILITIES

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16. Abstract

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SUMMARY

Data-reduction procedures for determining free-stream and post-normal-shock kinetic and thermodynamic quantities are derived. These procedures are applicable to imperfect real-air flows in thermochemical equilibrium for temperatures to 15 000 K and a range of pressures from 0.25 N/m^2 to 1 GN/m^2. Although derived primarily to meet the immediate needs of the Langley 6-inch expansion tube, these procedures are applicable to any supersonic or hypersonic real-air test facility where combinations of the following flow parameters are measured in the test section:

(1) Stagnation pressure behind normal shock

(2) Free-stream static pressure

(3) Stagnation-point heat-transfer rate

(4) Free-stream flow velocity

(5) Stagnation density behind normal shock

(6) Free-stream density

Nine data-reduction procedures resulting from various combinations of three of these measured flow parameters are derived. These procedures employ an adjustment of computed flow parameters by numerical iteration until measured and computed flow parameters are within a prescribed tolerance.

Because the above six flow parameters are measured in the test section, these procedures do not depend explicitly upon measured or calculated upstream flow parameters. The elimination of dependence on upstream flow conditions results in a reduction in the uncertainty in predicted test-section conditions.

Limitations of the various procedures and uncertainties in calculated flow quantities corresponding to uncertainties in measured input data are discussed. All nine procedures are incorporated into a single computer program written in FORTRAN IV language. A listing of this computer program is presented, along with a description of the inputs required and a sample of the data printout.

INTRODUCTION

Over the past decade, a number of studies (refs. 1 to 11) have been directed toward prediction of performance characteristics of expansion tubes and expansion tunnels. The initial theoretical study of the expansion tube was performed by Trimpi (ref. 1). In reference 1 a simplified flow model based on idealized processes was used. However, Trimpi acknowledged the possible existence of detrimental effects on expansion tube performance arising from real physical conditions (such as noninstantaneous primary- and secondary-diaphragm rupture, shock-wave attenuation, interface mixing, and flow turbulence). At the time reference 1 was written, the extent to which these possible phenomena deviated the actual flow from idealized flow remained to be determined experimentally. (The complexity associated with these real physical conditions generally prohibits rigorous theoretical treatment.) To this end, the Langley shock tunnel was modified in 1961 to serve as a pilot model expansion tube. Experimental results of exploratory studies in this facility are reported in references 12 and 13. As might be expected, significant differences between measured and theoretically predicted flow quantities were observed.

Investigations representing extensions of existing experimental studies into the high-velocity real-air regime will be performed in the Langley 6-inch expansion tube. To make meaningful comparisons of these real-air data with the existing data and corresponding correlations, accurate predictions of free-stream and post-normal-shock flow conditions are required.

The usual procedure for determining expansion tube test-section flow conditions (for real air in thermochemical equilibrium) is first to determine conditions behind the incident shock propagating into the static test gas within the intermediate section (see fig. 1). (The charts of ref. 14 are a convenient and often employed means of determining these conditions.) An isentropic unsteady expansion from the velocity of the shocked test gas in the intermediate section to the measured free-stream velocity at the test section is performed (ref. 3). With the free-stream flow conditions determined, the post-normal-shock conditions are determined from existing tables or charts for standing normal shocks. This scheme generally yields test-section flow quantities significantly different from measured quantities.

The purpose of this study is to provide a means for obtaining accurate test-section flow conditions in the expansion tube and expansion tunnel. The computational scheme used to predict test-section conditions is based on flow parameters measured in the test section, and thus an explicit dependence upon measured or calculated upstream flow parameters is eliminated. The elimination of dependence on upstream flow conditions should result in a substantial reduction in the uncertainty in predicted test-section conditions. (For example, it has been speculated in refs. 13 and 15 that one cause of failure of the theoretical approach in predicting test-section conditions is nonideal rupture of the upstream secondary diaphragm.) Such a computational scheme requires measurement of three flow quantities at the test section in order to satisfy the conservation equations for a standing normal shock. Presently, three test-section flow quantities are measured, on a routine basis, in the Langley 6-inch expansion tube:

(1) Stagnation pressure behind normal shock

(2) Tube wall static pressure

(3) Velocity of interface of acceleration gas and test gas

Another measurable flow quantity that will be obtained on a routine basis is stagnation-point heat-transfer rate. Stagnation-point heat-transfer rate measurements have been obtained successfully in shock tubes and shock tunnels with thin-film gages (e.g., refs. 16 to 18) and thick-film gages (e.g., refs. 19 and 20). Hence, these instrumentation techniques are applicable in the expansion tube (ref. 21). Stagnation-point heating rate has been employed as a basic input datum in data-reduction procedures for arc-heated impulse tunnels (commonly referred to as hotshot tunnels) as discussed in reference 22. Following the example of reference 22, the stagnation-point heating rate is included herein as a fourth basic input datum.

An additional flow quantity that can be inferred from experimental techniques is the density. Although free-stream density and stagnation-point density behind a normal shock are not presently measured in the Langley 6-inch expansion tube or expansion tunnel on a routine basis, these two quantities are, nevertheless, considered herein as input data.

From these six flow quantities measured at the test section, nine procedures for determining free-stream and post-normal-shock flow conditions are derived. These procedures utilize the thermodynamic properties for imperfect real air in thermochemical equilibrium as tabulated in references 23 and 24. (The results of refs. 23 and 24 represent a compilation of the air data of refs. 25 and 26, with interpolations and differentiation. They cover a range of temperatures from 100 K to 15 000 K and a range of pressures from 0.25 N/m^2 to 1 GN/m^2.) Although derived to meet the immediate needs of the Langley 6-inch expansion tube, these procedures are also applicable to supersonic or hypersonic test facilities with real-air flows.

Limitations of the procedures are discussed. An experimental uncertainty is assigned to each of the six experimental inputs and the corresponding uncertainty in calculated flow quantities is examined.

The relations considered for the prediction of stagnation-point heat-transfer rate for real air are discussed in appendix A. The transport properties for high-temperature air required in the prediction of stagnation-point heat-transfer rate are discussed in appendix B. The calculation schemes for the individual data-reduction procedures are presented in appendix C. All nine procedures are incorporated into a single computer program written in FORTRAN IV language. A listing of this computer program and a sample data printout are presented in appendix D, and a description of the inputs required is presented in appendix E.

SYMBOLS

The International System of Units (SI) is used for all physical quantities in this study. Conversion factors relating the SI Units to U.S. Customary Units are given in reference 27.

a	speed of sound, m/sec
c_p	specific heat at constant pressure, J/kg-K
D	diffusion coefficient, m^2/sec
h	specific enthalpy, m^2/sec^2 (J/kg)
h_C	convective heat-transfer coefficient, W/m^2-K
h_D	atomic dissociation energy, J/kg
k	thermal conductivity, W/m-K
M	Mach number, V/a
N_{Le}	Lewis number, $\rho c_p D/k$
N_{Nu}	Nusselt number, $h_C S/k$
N_{Pr}	Prandtl number, $\mu c_p/k$
N_{Re}	Reynolds number per meter, $\rho V/\mu$
p	pressure, N/m^2
$\dot{q}$	heat-transfer rate, W/m^2

R	universal gas constant, 8.31434 kJ/kmol-K
r_e	effective nose radius, m
r_g	geometric nose radius, m
S	distance along body measured from stagnation point, m
s/R	nondimensional specific entropy
T	temperature, K
V	velocity, m/sec
W	molecular weight, kg/kmol
W_o	molecular weight of undissociated air, 28.967 kg/kmol
Z	compressibility factor, $pW_o/\rho RT$
Z^*	ratio of number of moles to number of moles for undissociated air, W_o/W
β	stagnation-point velocity gradient, sec^{-1}
$\eta \equiv \rho c_p k$	
γ_E	isentropic exponent, $\left(\frac{\partial \log p}{\partial \log \rho}\right)_{s/R}$
μ	coefficient of viscosity, N-sec/m^2
ξ	nondimensionalized ratio of uncertainty in calculated flow quantity to corresponding uncertainty in input quantity (see eq. (9))
ρ	density, kg/m^3
τ	time, sec

Subscripts:

amb	ambient
av	average
c	calculated
low	lower limit
m	measured
prev	previous value of a parameter
S	based on distance along body from stagnation point
s	model surface material
t	stagnation conditions behind normal shock
up	upper limit
w	model wall
w,1	tube or nozzle wall
1	free stream
2	static conditions immediately behind normal shock

Superscripts:

α	order of iteration
$\sim$	approximate value

ANALYSIS

Several topics are presented before the discussion of the various calculation procedures for determining free-stream and post-normal-shock flow quantities. First a brief description of the Langley 6-inch expansion tube and expansion tunnel is given. This description is followed by a discussion of the instrumentation techniques employed to obtain the experimental data input required by the various calculation procedures. The magnitude of the uncertainties in the experimental data input is also discussed. The source of the thermodynamic properties for real air in thermochemical equilibrium employed in this study is discussed. Next, the methods for crossing the standing normal shock are discussed, since these methods are common to all calculation procedures. Finally, the relations used to predict stagnation-point heat-transfer rate are discussed briefly.

Description of Expansion Tube and Expansion Tunnel

The Langley 6-inch expansion tube is basically a cylindrical tube with a 15.24-cm inside diameter, divided by two diaphragms into three sections. The most upstream section is the driver or high-pressure section. This section is pressurized at ambient temperature with a gas having a high speed of sound, such as hydrogen or helium. (Greater operation efficiency is realized with gases having a high speed of sound; e.g., see ref. 28.) The pressure and speed of sound of the driver gas are increased further by heating the gas with a 3-MW resistance heater or utilizing an arc discharge into the gas from a 10-MJ capacitor bank. The intermediate section is usually referred to as the driven section. This section is evacuated and filled with the test gas at ambient temperature. The most downstream section is referred to as the expansion or acceleration section. This section is also evacuated and generally filled with helium at a low pressure and ambient temperature. For resistance heating of the driver gas, the driver and driven sections are separated by a double diaphragm apparatus capable of withstanding a maximum pressure differential of 68.95 MN/m^2. (By controlling the pressure level in the small chamber between these diaphragms, the time of diaphragm rupture can be controlled.) For arc heating, a single diaphragm is used between the driver and driven sections. A weak, low-pressure diaphragm (secondary diaphragm) separates the driven and acceleration sections. The test section and model are located at the downstream exit of the acceleration section.

The operating sequence, which is shown schematically in figure 1, begins with the rupture of the high-pressure diaphragm. A primary shock wave propagates into the static test gas and an expansion wave propagates into the driver gas. The shock wave then encounters and ruptures the low-pressure diaphragm. A secondary shock wave propagates into the low-pressure accelerating gas while an upstream expansion wave moves into the test gas. In passing through this upstream expansion wave, which is being washed downstream since the shock-heated test gas is supersonic, the test gas undergoes an isentropic unsteady expansion resulting in an increase in the flow velocity.

The expansion tunnel is simply an expansion tube with a nozzle added at the downstream end. Thus, the test gas is processed first by the primary shock in the intermediate section, then by an unsteady expansion in the acceleration chamber, and finally by an isentropic steady expansion in the nozzle (ref. 4).

Experimental Data

Pressure.- The expansion tube is characterized by extremely short test times. In general, the test time is less than 400 μsec, and thus the pressure instrumentation must have very fast response to pressure change and a minimum of orifice-cavity volume to reduce pressure-lag effects. Presently, stagnation pressure behind a normal shock (pitot pressure) and expansion tube or nozzle-wall pressure are measured with miniature piezoelectric (quartz) transducers having rise times of approximately 1 to 3 μsec and a pressure range of approximately 700 N/m^2 to 20 MN/m^2. The pressure transducers are used in conjunction with a charge amplifier, and the output signal is recorded from an oscilloscope with the aid of a camera.

Experimental uncertainties in such pressure measurements are dependent on many factors, such as pressure level with regard to transducer sensitivity, calibration technique (static or dynamic), transducer linearity, oscilloscope accuracy, quality of oscilloscope traces with respect to the signal-to-noise ratio, and data read-up procedure. Hence, a general assignment of the uncertainty in these pressure measurements is not possible. On the basis of previous experience, the maximum uncertainties in pressure measurements are believed to be less than ±20 percent for tube or nozzle-wall pressure and for pitot pressure.

Velocity.- The free-stream velocity is usually inferred by using a microwave technique. A microwave signal is propagated upstream into the acceleration section by means of an antenna mounted in the neighborhood of the acceleration-section exit (test section). The microwave signal is reflected from the interface, provided the electron concentration at the interface is high enough for reflection of the operating signal. (As shown in ref. 9, for incident shock velocities less than 10 km/sec in the helium acceleration gas, the helium is not ionized and is therefore transparent to the microwave signal.) The interference of the reflected wave with the transmitted wave provides a measurement of the interface velocity. The microwave signal is recorded on film by means of a combination of a high-speed drum camera and an oscilloscope. The uncertainty in measuring the interface velocity with this technique is believed to be less than ±2 percent. However, the experimental results of reference 29 show that the flow velocity is not uniform behind the interface, and inferring that the free-stream velocity is equal to the interface velocity may result in errors up to 5 percent for velocities around 6 km/sec. For the purposes of this study, the uncertainty in free-stream velocity (as inferred from microwave measurements) will be assumed not to exceed ±5 percent.

Stagnation-point heat-transfer rate.- Because of the heat-flux limitations of thin-film heat-transfer gages, thick-film or calorimeter heat-transfer gages are used to measure stagnation-point heat-transfer rates in the Langley 6-inch expansion tube. The thick-film gage consists of a thin-foil sensing element (usually pure platinum) mounted on an insulating substrate. The foil thickness is chosen so that only a negligible amount of heat is transferred to the substrate (generally less than 5 percent) during the testing period. A detailed theoretical treatment of the thick-film heat-transfer gage and data-reduction procedure is presented in reference 19. In reference 20, the experimental uncertainty for the thick-film heat-transfer gage is stated to be ±11 percent. Possible detrimental effects due to flow turbulence level and flow contamination, the magnitudes of which are unknown for the Langley 6-inch expansion tube, would tend to increase the uncertainty in stagnation-point heat-transfer measurements. For this study, the uncertainty in these measurements will be assumed not to exceed ±20 percent.

Density.- Free-stream density measurements have been made in the Langley pilot model expansion tube by using a spectroscopic method similar to that described in reference 30. These measurements, which are based on the light-absorption properties of oxygen molecules, are believed to have an uncertainty of approximately ±10 percent. For purposes of this study, the uncertainty in both free-stream density and stagnation-point density will be assumed not to exceed ±20 percent.

Thermodynamic Properties for Real Air

Thermodynamic properties for imperfect real air in thermochemical equilibrium are obtained from a magnetic tape furnished to the Langley Research Center by the Arnold Engineering Development Center (AEDC) in late 1965. The thermodynamic properties obtained from this tape correspond to the properties tabulated in reference 23 for various values of s/R. The temperature range of reference 23 and of the AEDC tape is 100 K to 15 000 K and the pressure range is 0.25 N/m^2 to 1 GN/m^2. For temperatures from 100 K to 1500 K, the results of reference 23 were obtained by interpolation of the data of reference 25; for temperatures from 1500 K to 15 000 K, the results were obtained by interpolation of the data of reference 26. In addition to the effects of dissociation and ionization, the high-temperature data of reference 26 include second virial corrections for interactions between neutral-neutral species and ion-neutral species. The low-temperature (undissociated) air composition of reference 26 is 78.084 percent N_2, 20.946 percent O_2, 0.934 percent Ar, 0.033 percent CO_2, and 0.003 percent Ne by volume. This composition corresponds to a molecular weight of 28.967.

Thermodynamic properties included on the composite AEDC tape are a, h, p, s/R, T, Z, Z^*, γ_E, and ρ. The properties a and γ_E correspond to those tabulated in reference 31 for temperatures from 1500 K to 15 000 K. The results of reference 31 were obtained by interpolation and differentiation of the real-air data of reference 26.

As obtained from AEDC, the subroutine for searching the real-air tape required inputs of s/R in conjunction with one of the following thermodynamic properties: a, h, p, T, ρ. (The procedure whereby a, h, p, T, or ρ is used in conjunction with s/R for inputs to the AEDC tape is designated herein as SLOW.) An interpolation procedure allowing combinations of h, p, and ρ as inputs to the AEDC tape was derived for this study. This interpolation procedure is referred to herein as SEARCH (L), where $L = 1$ denotes inputs h and p, $L = 2$ denotes inputs p and ρ, and $L = 3$ denotes inputs h and ρ.

The relations derived in reference 32 for predicting thermodynamic properties of real air in thermochemical equilibrium were also employed in the present study. These relations were obtained from curve fits to the real-air results of references 25, 33, and 34, and cover a temperature range of 90 K to 15 000 K. Imperfect air (intermolecular force) effects are neglected in reference 32. The maximum percentage errors in the results of these relations for a pressure range of 10 to 1000 kN/m^2 and temperature range of 2000 K to 15 000 K are (ref. 32):

a, percent	2.78
h, percent	1.96
T, percent	2.24
Z, percent	0.75
γ_E, percent	≈5.00
ρ, percent	2.52

These relations, in which the independent variables are p and s/R, are incorporated into a subroutine designated herein as SAVE (K). This subroutine utilizes an iteration-interpolation scheme allowing combinations of h, p, s/R, and ρ as inputs; $K = 1$ denotes inputs p and s/R, $K = 2$ denotes inputs p and ρ, $K = 3$ denotes inputs p and h, and $K = 4$ denotes inputs h and ρ.

Iterative Procedure for Standing Normal Shock

The conservation relations for mass, momentum, and energy for a standing normal shock are

$$\rho_1 V_1 = \rho_2 V_2 \tag{1}$$

$$p_1 + \rho_1 V_1^2 = p_2 + \rho_2 V_2^2 \tag{2}$$

$$h_1 + \frac{1}{2} V_1^2 = h_2 + \frac{1}{2} V_2^2 \tag{3}$$

Both the direct solution and the inverse solution to the conservation relations were used in this study. The direct solution requires the free-stream flow conditions, including flow velocity, as inputs and yields the postshock static and stagnation conditions. The inverse solution requires postshock flow conditions as inputs and yields the free-stream conditions. The direct solution is generally employed when at least two of the required three inputs are free-stream conditions, and the inverse solution is employed when at least two of the required three inputs are postshock conditions. Both solutions will now be discussed.

Direct solution.- In the direct solution, the free-stream flow conditions appearing on the left side of equations (1) to (3) are considered known. To solve for the four unknown postshock static conditions $(\rho_2,\ V_2,\ p_2,$ and $h_2)$, an additional relation is required, the equation of state in the form of SEARCH (L) or SAVE (K). (Either SEARCH (L) or SAVE (K) may be used as the equation of state. In the subsequent discussion SEARCH (L) will be used, except in cases where relatively accurate initial estimates of thermodynamic properties are required, for which SAVE (K) is preferable.)

The iterative procedure for the direct solution begins by first estimating a value of ρ_2. This value of ρ_2 is used in equation (1) to yield a value of V_2. Then p_2 is found from equation (2) and h_2 from equation (3). These values of p_2 and h_2 are used as inputs to SEARCH (1) to obtain a value of ρ_2. This ρ_2 from SEARCH (1) is compared with the initial estimate of ρ_2. If these values of ρ_2 are not within 0.1 percent, the ρ_2 obtained from SEARCH (1) is used in equations (1) to (3) to obtain new values of V_2, p_2, and h_2. This procedure, commonly referred to as the method of successive approximations, is repeated until successive values of ρ_2 obtained from SEARCH (1) are within 0.1 percent.

The number of iterations in the method of successive approximations is dependent upon the accuracy of the initial estimate of ρ_2. Hence, a means for providing an accurate initial estimate of ρ_2 was examined. Since the free-stream conditions are assumed to be known in the direct solution, the stagnation enthalpy can be determined from the relation

$$h_t = h_1 + \frac{1}{2} V_1^2 \tag{4}$$

If measured p_t is not available, the relation

$$p_t = C\rho_1 V_1^2 \tag{5}$$

is used to estimate p_t. The factor C for real air may vary from approximately 0.93 to 1.0 (ref. 35). In this study, C was taken to be 0.965.

With a known p_t value or estimated (within ±3.5 percent) value from equation (5) and a known h_t, a relatively accurate value of ρ_t is obtained from SAVE (3). The initial estimate of ρ_2 is taken as

$$\rho_2 = 0.955\rho_t \tag{6}$$

In general, two to five iterations are required for this method of successive approximations.

The postshock stagnation conditions are determined by assuming that the flow region extending from immediately behind the normal shock to the stagnation point is isentropic $\left(\text{that is, } s_t/R = s_2/R\right)$. The calculated p_t is obtained by using s_t/R and h_t as inputs to SLOW. Other stagnation-point thermodynamic properties of interest are obtained by using h_t and p_t as inputs to SEARCH (1).

For the case where SAVE (K) is used to obtain postshock stagnation conditions, a value of p_t is estimated from the ideal-gas isentropic relation (ref. 36):

$$\tilde{p}_t = p_2\left(1 + \frac{\gamma_{E,2} - 1}{2} M_2^2\right)^{\gamma_{E,2}/\left(\gamma_{E,2}-1\right)} \tag{7}$$

Since the flow in the region extending from immediately downstream of the shock to the stagnation point can be considered to behave as an "ideal" gas $\left(\gamma_{E,2} \approx \gamma_{E,t} \text{ and } Z_2 \approx Z_t\right)$, $\tilde{p}_t$ from equation (7) is relatively accurate. Hence, values of p_t within 5 percent of $\tilde{p}_t$ are used along with s_2/R as inputs to SAVE (1), and corresponding values of $\tilde{h}_t$ are obtained. Since h_t is known, an interpolation is performed to obtain the desired p_t.

For convenience, this iterative procedure for determining postshock static and stagnation-flow conditions will be referred to hereafter as DIRECT.

Inverse solution.- The postshock conditions serving as inputs in the various procedures are inferred h_t from stagnation-point heat-transfer rate measurement, measured p_t, and measured ρ_t. For procedures having h_t and p_t as inputs, the corresponding stagnation conditions are obtained from SEARCH (1). Procedures having p_t and ρ_t as inputs utilize SEARCH (2) to obtain corresponding stagnation conditions. (Procedures having h_t and ρ_t as inputs are not included in this study.)

The flow region behind the shock is assumed to be isentropic; hence s_2/R is known. An initial estimate of p_2 is made and used with s_2/R as input to SLOW to obtain ρ_2 and h_2. The corresponding V_2 is found from the energy equation

$$V_2 = \sqrt{2\left(h_t - h_2\right)} \tag{8}$$

In the data-reduction procedures using the inverse solution, either p_1 or ρ_1 is known. Thus, the free-stream quantities appearing on the left side of equations (1) to (3) can be determined. The p_1 and h_1 values are used as inputs to SEARCH (1) to obtain a value of ρ_1. This ρ_1 from SEARCH (1) is compared with the measured or calculated ρ_1, and if not within the desired tolerance, the value of p_2 is varied and the procedure repeated. This numerical iteration on p_2 is continued until the condition on ρ_1 is satisfied.

Because of the relative insensitivity of p_2 to variations in free-stream flow conditions, this inverse shock-crossing procedure generally requires a larger number of iterations than the direct solution. Thus, it is desirable that the limits of p_2 required in this iteration be chosen so as to minimize computer time. For most tests in the expansion tube, the limits on p_2 will lie between

$$\left(p_2\right)_{up} = 0.97p_t$$

$$\left(p_2\right)_{low} = 0.85p_t$$

These limits are applicable for ideal-air free-stream Mach numbers greater than 3 or so. For Mach numbers less than 3, the lower limit of p_2 must be decreased to insure that the actual p_2 lies between these limits on p_2. (In the interest of computer time, the user is urged to adjust these limits so as to minimize the range of iteration on p_2 for his particular problem.)

This iteration procedure for determining postshock and free-stream flow conditions will be referred to hereafter as INVERSE.

Prediction of Stagnation-Point Heat-Transfer Rates

Over the past two decades, considerable effort has been directed toward obtaining relations for predicting stagnation-point heat-transfer rates at high flight velocities. Consequently, the literature contains numerous theoretical procedures for determining laminar stagnation-point heating rates for blunt axisymmetric bodies. However, as noted in references 37 and 38, the scatter in experimental data obtained at velocities greater than 6.1 km/sec prohibits identification of the least uncertain theoretical procedures.

Because measured $\dot{q}_t$ is considered as a basic input datum, an accurate means of predicting $\dot{q}_t$ must be utilized. Hence the theoretical results of references 39 to 43 for predicting $\dot{q}_t$ on blunt axisymmetric bodies are examined, along with the empirical relation of reference 44. (The results of these studies are discussed in appendix A.) As noted in reference 45, uncertainties in transport properties of high-temperature air represent a source of discrepancies in the various theoretical relations for predicting $\dot{q}_t$. Thus, the results of references 46 to 48 concerning transport properties of high-temperature air are discussed briefly in appendix B.

Procedures for Determining Free-Stream and Postshock Flow Conditions

The procedures for determining free-stream and post-normal-shock flow conditions are identified in the computer program as ITEST. For convenience, this method of identification will be employed in the following discussion.

The basic measured inputs and iterative procedure for crossing the normal shock are given in the following table:

ITEST	Measured inputs	Shock-crossing procedure
1	p_t, p_1, V_1	Direct
2	$p_t, \dot{q}_t, V_1$	Direct
3	$p_t, \dot{q}_t, p_1$	Inverse
4	$\dot{q}_t, V_1, p_1$	Direct
5	p_1, ρ_1, V_1	Direct
6	p_1, ρ_1, p_t	Direct
7	p_t, ρ_t, ρ_1	Inverse
8	p_t, ρ_t, p_1	Inverse
9	p_t, ρ_t, V_1	Direct

In these procedures calculated and measured flow quantities are compared, and if the calculated quantities are not within a prescribed tolerance of the measured quantities, a numerical iteration is performed. This iteration results in an upgrading of the calculated flow quantity until satisfactory agreement between calculated and measured values is obtained. The prescribed tolerance established for iteration is, of course, somewhat arbitrary. For example, in general usage of these procedures for the expansion tube, the calculated p_t is required to be within 1 percent of the measured p_t. Refining this tolerance to a smaller value is not believed warranted, considering the experimental uncertainty in measured p_t. However, in real-air facilities where p_t can be measured with a high degree of confidence, the user of these data-reduction procedures may wish to define the tolerances for iteration. Hence, the tolerances for iteration on the measured quantities p_t, $\dot{q}_t$, and ρ_1 are treated as inputs and the user can establish his own degree of refinement on these iterations. The tolerance on measured p_t is denoted by TOLPT, that on measured $\dot{q}_t$ by TOLQT, and that on measured ρ_t by TOLRHO.

In the case of the expansion tube, the free-stream static pressure is assumed to be equal to the measured tube wall pressure $\left(\text{that is, } p_1 = p_{w,1}\right)$. This assumption is subject to question. As discussed in reference 49, a number of experimental studies have shown that the measured wall static pressure is greater than the static pressure at the edge of a turbulent boundary layer. These studies indicate that $p_{w,1}/p_1$ becomes increasingly greater than 1 as Mach number increases. For air and nitrogen flows, $p_{w,1}/p_1$ is less than approximately 1.1 when M_1 is less than 10; however, when M_1 is about 20, $p_{w,1}$ may be as much as twice p_1 (ref. 49). Because of the inherent differences between conventional wind tunnels and the expansion tube (particularly in regard to test time), the questionable state of the expansion tube wall boundary layer (laminar, transitional, or turbulent), and the lack of a correlation for $p_{w,1}/p_1$, no attempt is made to adjust p_1.

The calculation scheme for the individual procedures (ITEST) is discussed in appendix C.

DISCUSSION

Because of the greater simplicity associated with procedure ITEST = 5, this procedure was the first to be programed for computer usage. For debugging purposes, cases were run with ITEST = 5 which covered a T_t range of 1200 K to 14 000 K. The charts of reference 50 were used, where applicable, to provide a rough check on the computed flow parameters. After the debugging process for ITEST = 5, several cases were run and the results were compared with the recent results of reference 51. In all cases, the free-stream and postshock flow conditions agreed with those of reference 51 to within 1 percent. (The T_t range corresponding to these comparison cases was 1500 K to 13 000 K.) Following the successful check of ITEST = 5, the remaining eight procedures were programed and a common check case was run for each procedure. For these check cases the free-stream inputs were the same as those employed with ITEST = 5, but the postshock outputs p_t, ρ_t, and $\dot{q}_t$ of ITEST = 5 were used as inputs. In the check cases of the various procedures, TOLPT = TOLQT = TOLRHO = 0.001. For these tolerances of iteration, the computed flow quantities for all eight procedures were observed to be in excellent agreement with those of ITEST = 5.

The ITEST = 5 procedure was used to run a number of cases in which values of $\dot{q}_t$ were calculated from the theoretical findings of references 39 to 43 and the empirical result of reference 44. Included in these cases was a 15.24 km/sec entry trajectory for a vehicle having a lift-drag ratio of 1. The velocity range considered for this entry trajectory was 1.5 to 12.2 km/sec and the corresponding altitude range was 36.6 to 61 km. The results for this entry trajectory are shown in figure 2, where $\dot{q}_t$ is plotted as a function of V_1. The value of T_w was held at 300 K and r_g (for a sphere) was 1.27 cm. The T_t value corresponding to V_1 and to the thermodynamic conditions at the corresponding altitude can be found from the scale at the top of figure 2. Except for reference 41, the source of transport properties used in the derivation of the various theoretical results was also used for the predicted $\dot{q}_t$ of figure 2. Instead of using Sutherland's viscosity relation in the method of reference 41, μ_t was obtained from reference 46.

At the lowest V_1 value of figure 2 there should be little, if any, difference in transport properties used in references 39 to 43. For this V_1 the result of reference 44 is approximately 1.2 times the average of the five theoretical results $\left(\dot{q}_t\right)_{av}$. As V_1 increases, the difference between $\dot{q}_t$ from reference 44 and $\left(\dot{q}_t\right)_{av}$ decreases. The μ_t results of reference 46 are believed to be too low for T_t values between 1500 K and 8000 K (see appendix B); hence, if the more accurate μ_t results of reference 47 are employed in references 39, 41, and 42, $\left(\dot{q}_t\right)_{av}$ will increase. Between velocities of 4.5 and 9 km/sec, the magnitude of this increase is such as to bring $\left(\dot{q}_t\right)_{av}$ into good agreement with the result of reference 44. At velocities above 9 km/sec (corresponding to $T_t > 8000$ K), the uncertainty in transport properties increases because of ionization phenomena. For V_1 values from 9 to 12 km/sec, the μ_t of reference 46 is still conservative in comparison with that of reference 47; hence, use of the results of reference 47 would increase $\left(\dot{q}_t\right)_{av}$. This $\left(\dot{q}_t\right)_{av}$ would then be greater than the $\dot{q}_t$ of reference 44 for this velocity range.

In this study, the empirically based result of reference 44 for predicting $\dot{q}_t$ was decided upon for $T_t \geqq 4500$ K. This corresponds to V_1 greater than approximately 4.5 km/sec in figure 2. (Although ref. 44 may be somewhat conservative for $V_1 > 9$ km/sec, the uncertainty in transport properties at these conditions precludes modification of ref. 44 or adoption of another source for predicting $\dot{q}_t$.) For $T_t < 4500$ K, the result of reference 41 (with $N_{Le} = 1$) was adopted, where μ_t is obtained from reference 47.

The uncertainties in calculated flow quantities due to uncertainties in experimental inputs were examined. For each procedure, one of the inputs was varied (simulating a measurement error) while the remaining two inputs were held constant. Hence, the sensitivity of the calculated flow quantities to this variation in a given input was determined. The results of this error analysis are shown in figure 3, where the error parameter ξ

is plotted for various free-stream quantities and stagnation-point quantities of interest. The parameter ξ is defined as

$$\xi \equiv \left(\frac{\theta_{error} - \theta_{correct}}{\phi_{error} - \phi_{correct}}\right)\frac{\phi_{correct}}{\theta_{correct}} \tag{9}$$

where θ represents the calculated flow quantity of interest and ϕ represents the experimental input quantity. The "correct" inputs used in obtaining the results of figure 3 correspond to a representative expansion tube test with a heated helium driver at moderate driver pressure (16.5 MN/m^2). (Values for the "correct" free-stream and postshock flow conditions are given in the sample printout of appendix D.) The ϕ_{error} was less than or equal to 5 percent for the results of figure 3. The tolerances of iteration used in obtaining these results were TOLPT = TOLRHO = 0.001 and TOLQT = 0.005.

As observed from figure 3, the degree of uncertainty in calculated flow conditions corresponding to an uncertainty in experimental inputs varies for the different ITEST procedures. Naturally, the type of investigation being conducted in a facility would dictate what flow quantities are most important and what limits of uncertainty in these quantities can be tolerated. (For example, $N_{Re,1}$ is an important parameter in most viscous flow studies but is of relatively little importance in stagnation-point radiative heating studies.) For purposes of illustration, let it be assumed that all the free-stream quantities shown on the abscissa of figure 3 are pertinent to a given investigation. The degrees of uncertainty in calculated free-stream quantities for the various procedures can be roughly compared by allowing the maximum uncertainty permissible in any of the calculated free-stream quantities of figure 3 to be some value, say 20 percent or so. For the representative expansion tube test under consideration, the approximate maximum uncertainty permitted in each input (where the remaining two inputs are assumed to be correct) for each procedure is as follows:

ITEST	Maximum uncertainty, percent, in input —					
	p_1	V_1	p_t	$\dot{q}_t$	ρ_1	ρ_t
1	20	8	12	---	---	---
2	---	.5	2	1	---	---
3	20	----	7	18	---	---
4	20	2	---	5	---	---
5	20	20	---	---	12	---
6	20	----	42	---	18	---
7	---	----	2	---	1	1
8	20	----	36	---	---	10
9	---	.5	1	---	---	1

Hence, for a study at the conditions given in the sample printout of appendix D, if all the free-stream quantities of figure 3 are considered pertinent, procedures ITEST = 1, 3, 5, 6, and 8 are preferable to ITEST = 2, 4, 7, and 9. If the pertinent quantities for an investigation are the stagnation-point quantities of figure 3, the relative preferability of the procedures is not nearly so obvious. This is illustrated by the following table, where the maximum uncertainty permissible in any of the calculated stagnation-point quantities of figure 3 was taken as 20 percent or so:

ITEST	Maximum uncertainty, percent, in input –					
	p_1	V_1	p_t	$\dot{q}_t$	ρ_1	ρ_t
1	>>20	10	20	---	----	---
2	----	>>5	15	35	----	---
3	>>20	-----	15	35	----	---
4	>>20	3.5	---	8	----	---
5	>>20	7	---	---	20	---
6	>>20	-----	13	---	20	---
7	----	-----	10	---	>>20	11
8	>>20	-----	10	---	----	12
9	----	>>5	10	---	----	11

Error analyses were also performed for procedures ITEST = 1, 3, and 5 for the same free-stream thermodynamic inputs that are shown in the sample printout of appendix D, but at stagnation conditions corresponding to V_1 values of 3 and 12 km/sec. (Procedures ITEST = 1, 3, and 5 were chosen because these are expected to be used for most of the data reduction in the Langley 6-inch expansion tube.) The ratio $\frac{\theta_{error}}{\theta_{correct}}$ for both velocities (3 and 12 km/sec) was observed to be essentially the same as for the representative expansion tube test case considered previously for a velocity of 6.1 km/sec.

In a program such as that presented herein, computer time is of concern. The procedures were run individually on a Control Data 6600 series computer for the representative expansion tube test case used in the error analysis. The total time (computational and peripheral) for each procedure, when the thermodynamic properties were obtained from the AEDC tape (that is, SAVE (K) was not utilized), is given in the following table:

ITEST	Total time, sec
1	580
2	490
3	375
4	570 (1200)
5	240
6	340
7	440
8	530
9	420

These times were obtained with TOLPT = TOLQT = TOLRHO = 0.005 and the iteration limits presented herein. The total time of 570 seconds for ITEST = 4 corresponds to the refined limits on ρ_1 for M_1 greater than approximately 8; the total time of 1200 seconds corresponds to the more general limits on ρ_1. (See appendix C.)

Although these total times for procedures employing DIRECT should be fairly representative for the stated iteration tolerances, the time for procedures employing INVERSE (ITEST = 3, 7, and 8) should not. This is because $p_2/p_t = 0.959$ for the example test case under consideration. Since the iteration procedure on p_2 in INVERSE begins with the upper limit on p_2 $\left((p_2)_{up}/p_t = 0.97\right)$, the total times in the table above for ITEST = 3, 7, and 8 are believed to be somewhat less than that corresponding to the general case.

The relatively large computer times associated with the data-reduction procedures presented herein are due primarily to the time required for tape manipulation. This conclusion was verified by examining the total time required by SEARCH (L). Cases were run for L = 1, 2, and 3. For a single usage of SEARCH (L), the total time required ranged from 34 seconds for L = 2 and 3 to 52 seconds for L = 1. These same cases were also run with SLOW. Multiple callings of SLOW were performed in order to obtain the same thermodynamic properties as were obtained with SEARCH (L). The total time was 28 seconds. Hence, it is obvious that repetitive usage of SEARCH and SLOW, as required in the iterations of the present procedures, will consume a large amount of total computer time.

Subroutine SAVE (K), which is based on the real-air curve-fit expressions of reference 32, was incorporated into the present data-reduction procedures in an attempt to reduce computer time and tape usage. This subroutine replaces the subroutines SLOW and SEARCH (L), which were written to search the AEDC real-air tape, as the source of real-air thermodynamic properties. Some loss in accuracy is incurred in using

SAVE (K), particularly at high densities where intermolecular force effects become important. (See section entitled "Thermodynamic Properties for Real Air.") However, these data-reduction procedures based on SAVE (K) should be sufficiently accurate for most purposes. The nine procedures, now divorced from the AEDC tape, were run individually on the computer for the same representative expansion tube case and same iteration tolerances used in the previous time study. For each procedure the computer time was much less than when the AEDC tape was used. For example, the 1200 seconds required for ITEST = 4 with subroutines SLOW and SEARCH (L) was reduced to 40 seconds with subroutine SAVE (K). Thus, the problem of relatively large computer times is circumvented by usage of SAVE (K) without sacrificing appreciable accuracy.

CONCLUDING REMARKS

Data-reduction procedures for determining free-stream and post-normal-shock kinetic and thermodynamic quantities are derived. These procedures are applicable to imperfect real-air flows in thermochemical equilibrium for temperatures to 15 000 K and a range of pressures from 0.25 N/m^2 to 1 GN/m^2. Nine data-reduction procedures resulting from various combinations of three of the following measured flow parameters were derived:

(1) Stagnation pressure behind normal shock

(2) Free-stream static pressure

(3) Stagnation-point heat-transfer rate

(4) Free-stream flow velocity

(5) Stagnation density behind normal shock

(6) Free-stream density

The various combinations of measured flow parameters are identified herein as ITEST and are:

ITEST	Measured flow parameter
1	(1), (2), (4)
2	(1), (3), (4)
3	(1), (2), (3)
4	(2), (3), (4)
5	(2), (4), (6)
6	(1), (2), (6)
7	(1), (5), (6)
8	(1), (2), (5)
9	(1), (4), (5)

These procedures employ an adjustment of computed flow parameters by numerical iteration until measured and computed flow parameters are within a prescribed tolerance. All nine procedures are incorporated into a single computer program written in FORTRAN IV language.

The uncertainties in calculated flow quantities due to uncertainties in the experimental inputs were examined. This error analysis demonstrated that for an investigation in which free-stream quantities (including Reynolds number) were pertinent, procedures ITEST = 1, 3, 5, 6, and 8 are preferable to ITEST = 2, 4, 7, and 9.

Relatively large computer times were observed for these procedures. The large times are due, primarily, to the time required in searching the real-air tape. Significant reduction in computer time, without appreciable loss of accuracy, was obtained by using real-air curve-fit expressions as the source of thermodynamic properties in place of the tape.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., February 11, 1972.

APPENDIX A

RELATIONS FOR PREDICTING STAGNATION-POINT HEAT-TRANSFER RATES

In the present study the theoretically derived expressions of references 39 to 43 for predicting stagnation-point heat-transfer rates on blunt axisymmetric bodies were examined. The results of these five theoretical studies are discussed in this appendix, and the empirical stagnation-point heat-transfer relation of reference 44 is presented.

Cohen

From correlations of numerical results, Cohen (ref. 39) obtained the relation

$$\dot{q}_t = 0.767\left(N_{Pr,w}\right)^{-0.6}\left(\rho_t\mu_t\right)^{0.43}\left(\rho_w\mu_w\right)^{0.07}\left(h_t - h_w\right)\sqrt{\beta}\left[1 + 0.075\left(\frac{h_t}{1.9686 \times 10^7} - 2\right)^2 \epsilon\right] \qquad (10)$$

for predicting stagnation-point heat-transfer rate. Cohen considered two free-stream velocity regimes in the derivation of equation (10). In the lower velocity regime, where the velocity was less than 8.84 km/sec, the air was assumed to be an equilibrium mixture of oxygen and nitrogen atoms and molecules. The transport properties for this equilibrium dissociated air were taken from the correlations of reference 52. In this lower velocity regime the results were obtained for wall temperatures from 300 K to 1750 K, and equation (10) represents the numerical solutions to within approximately ±5 percent. In the upper velocity range, where the velocity was from 8.84 to 12.5 km/sec, the transport properties of Hansen (ref. 46) were used by Cohen. Results were obtained for wall temperatures to 5200 K, and equation (10) represents the numerical solutions for this regime to within approximately ±10 percent.

In the present study, the thermodynamic quantities ρ_t and h_t appearing in equation (10) are obtained from the AEDC real-air tape. The value of μ_t is obtained from reference 46 or 47. (Further discussion concerning the obtainment of μ_t is presented in appendix B.) The parameter ϵ appearing in equation (10) distinguishes the velocity regime. For the lower velocity regime (to 8.84 km/sec), $\epsilon = 0$; for the upper velocity regime (8.84 to 12.5 km/sec), $\epsilon = 1$.

Because of the very short test time of the expansion tube, the wall temperature remains on the order of ambient temperature. Hence, the wall temperature can be set equal to the ambient temperature, as was done in reference 22, or can be estimated. To obtain a rough estimate of T_w, the assumption is made that the thick-film heat-transfer gage used to measure stagnation-point heat-transfer rate experiences uniform flow. This results in a constant heat flux during the test time. Then, from reference 17, the wall temperature is given by the expression

$$T_w = 2\dot{q}_t\sqrt{\frac{\tau}{\pi\eta_s}} + T_{amb} \tag{11}$$

(This expression was derived from the one-dimensional heat-conduction equation for a homogeneous semi-infinite slab.)

Since T_w remains on the order of T_{amb}, the viscosity at the wall is obtained from Sutherland's expression (ref. 46):

$$\mu = 1.462 \times 10^{-6} \frac{\sqrt{T}}{1 + \frac{112}{T}} \tag{12}$$

The density at the wall is determined from the equation of state,

$$\rho_w = \frac{p_t W_o}{RT_w} \tag{13}$$

and the static wall enthalpy from the ideal-air expression,

$$h_w = 3.5 \frac{R}{W_o} T_w \tag{14}$$

It should be noted that in most cases $h_t >> h_w$, and too, the dependence of equation (10) on $\rho_w\mu_w$ is to the 0.07 power. Hence, the stagnation-point heat-transfer rate obtained from equation (10) has a weak dependency on wall temperature. For the range of T_w expected in expansion tube or expansion tunnel testing, relatively large errors in T_w would not be expected to have a significant effect on the calculated stagnation-point heat-transfer rate.

The stagnation-point velocity gradient was calculated from the modified Newtonian relation

$$\beta = \frac{1}{r_g}\sqrt{\frac{2(p_t - p_1)}{\rho_t}} \tag{15}$$

for axisymmetric bodies having a nose radius r_g.

Because of the relatively small range of T_w expected in the expansion tube or tunnel, the Prandtl number at the wall was assumed to be a constant and was set equal to 0.71.

Hoshizaki

Hoshizaki (ref. 40) correlated his numerical results to within ±6 percent, deriving the relation

$$\dot{q}_t = 1.1672\sqrt{\beta\rho_w\mu_w T_w{}^{0.4}}\, V_1{}^{1.69}\left(1 - \frac{h_w}{h_t}\right) \tag{16}$$

According to reference 40, this relation is valid for velocities from 1.83 to 15.2 km/sec, stagnation pressures between 100 N/m^2 and 10 MN/m^2, and wall temperatures from 300 K to 3000 K. The boundary layer at the stagnation point is assumed to be in thermochemical equilibrium. The effects of dissociation and ionization are taken into account by use of the total thermodynamic and transport property concept. In this concept, the properties are defined in such a way that the effects of dissociation and ionization are contained within them. The calculations of Hoshizaki are based on the transport properties of Hansen (ref. 46) for viscosity and allow the Prandtl number and Lewis number to vary. Methods employed herein for determining the various quantities appearing in equation (16) were discussed in the preceding section.

Fay and Riddell

Fay and Riddell (ref. 41) obtained, from correlation of numerical results, the expression

$$\dot{q}_t = 0.76\left(N_{Pr,w}\right)^{-0.6}\left(\rho_t\mu_t\right)^{0.4}\left(\rho_w\mu_w\right)^{0.1}\left(h_t - h_w\right)\sqrt{\beta}\left[1 + \left(N_{Le}{}^{0.52} - 1\right)\frac{h_D}{h_t}\right] \tag{17}$$

for predicting stagnation-point heat-transfer rate for dissociated air in thermochemical equilibrium. These results were restricted to a wall Prandtl number of 0.71; wall Lewis numbers of 1.0, 1.4, and 2.0; wall temperatures from 300 K to 3000 K; and velocities from 1.77 to 6.95 km/sec. The viscosity used in reference 41 was obtained by using Sutherland's expression (eq. (12)).

In reference 38, a semiempirical modification of Fay and Riddell's theory is suggested to extend it to higher velocities where the effects of ionization become important. Lewis and Burgess (ref. 38) compared the theory of Fay and Riddell for equilibrium nitrogen (for nitrogen, the factor 0.76 in eq. (17) is replaced by 0.754) and $N_{Le} = 1.0$ with the results of Fay and Kemp (ref. 53). Fay and Kemp utilized a simplified binary diffusion model of an ionized diatomic gas to obtain the transport properties for nitrogen. The calculations of reference 53 were performed for a wall temperature of 300 K, and a Lewis number of 0.6 was employed in most of the calculations. The comparison of Lewis and Burgess (ref. 38) showed that if the results of Fay and Riddell are simply multiplied by 1.15, they are in good agreement with the theory of Fay and Kemp (which includes ionization effects) for velocities in nitrogen from 6.1 to 16.78 km/sec. However, on the basis of the summary plot of reference 38, the present authors do not believe such a semiempirical modification to the theory of Fay and Riddell is justified for this study. Instead, it is felt that the theory of Fay and Riddell for equilibrium air and a Lewis number of 1 provides a "compromise" means for estimating the stagnation-point heat-transfer rate for velocities to 13.7 km/sec. (This conclusion is based on a comparison of curve 1 with the experimental data in the summary figure of ref. 38.)

The quantities appearing in equation (17) for $N_{Le} = 1$ are determined in the same manner as those in equation (10) derived by Cohen.

Pallone and Van Tassell

From a correlation of numerical results, Pallone and Van Tassell (ref. 42) derived the relation

$$\dot{q}_t = 0.90\left(N_{Pr,w}\right)^{-0.75}\left(\rho_t\mu_t\right)^{0.43}\left(\rho_w\mu_w\right)^{0.07}\left(h_t - h_w\right)\sqrt{\beta}\Lambda \qquad (18)$$

where for $V_1 \leqq 9.906$ km/sec, $\Lambda = 1$, and for $V_1 > 9.906$ km/sec,

$$\Lambda = \frac{V_1}{9906}$$

The parameter Λ represents a velocity dependence of the boundary-layer solutions for velocities in excess of 9.906 km/sec. Above velocities of 12.5 km/sec, a slight dependence on stagnation-point pressure was also observed. The calculations of Pallone and Van Tassell for air are also based on the transport properties of Hansen (ref. 46). Methods employed for determining the various quantities appearing in equation (18) were discussed previously.

DeRienzo and Pallone

The primary objective of this more recent study by DeRienzo and Pallone (ref. 43) was to extend the results of reference 42 to flight speeds as high as 21.3 km/sec. Unlike the studies of references 39, 40, and 42, this study (ref. 43) utilized the more recent transport properties of reference 47. Calculations were performed for velocities from 1.52 to 21.3 km/sec and included the effects of blowing. The numerical results of reference 43 are given in table I of that reference. To obtain expressions for calculating the stagnation-point heating rate, these tabulated results were correlated by the present authors for the case of an axisymmetric body with no blowing, stagnation-point pressures of 0.1 and 1 MN/m^2, and a velocity range of 1.52 to 12.2 km/sec. The results of reference 43 were correlated to within 5 percent by the expression

$$\frac{N_{Nu,w}}{\sqrt{N_{Re,w,S}}} = 0.62\left(\frac{\rho_t \mu_t}{\rho_w \mu_w}\right)^{0.3376} \tag{19}$$

for the heat-transfer parameter. The basic relation for $\dot{q}_t$ is (ref. 54).

$$\dot{q}_t = N_{Pr,w}^{-1} \frac{N_{Nu,w}}{\sqrt{N_{Re,w,S}}} \sqrt{\rho_w \mu_w \beta}\left(h_t - h_w\right) \tag{20}$$

and substituting equation (19) into equation (20) yields the expression

$$\dot{q}_t = 0.62 N_{Pr,w}^{-1}\left(\rho_t \mu_t\right)^{0.3376}\left(\rho_w \mu_w\right)^{0.1624}\left(h_t - h_w\right)\sqrt{\beta} \tag{21}$$

For velocities from 12.2 to 21.3 km/sec, the results of reference 43 were correlated to within 5 percent and the heat-transfer parameter was found to be

$$\frac{N_{Nu,w}}{\sqrt{N_{Re,w,S}}} = 0.465\left(\frac{\rho_t \mu_t}{\rho_w \mu_w}\right)^{0.205} \tag{22}$$

The value of μ_t in equations (21) and (22) is obtained from a numerical interpolation of the viscosity data of reference 47.

Zoby

In reference 44, Zoby presents a simple empirical relation for predicting stagnation-point heat-transfer rates in several gas mixtures, including air. This relation has the form

$$\dot{q}_t = \sqrt{\frac{p_t}{r_e}}\, K_i\left(h_t - h_w\right) \tag{23}$$

where r_e is the effective nose radius and K_i is a constant intended to account for the effect of thermodynamic and transport properties of the gas at the wall and external to the boundary layer. The constant K_i was determined in reference 44 by fairing a straight line through results of prediction methods and experimental measurements on a plot of $\dot{q}_t\sqrt{r_e/p_t}$ as a function of $h_t - h_w$.

The effective nose radius is defined in reference 55 as the hemispherical radius which produces the same velocity gradient as that computed for a blunt body which is not hemispherical. Since hemispherical heat-transfer probes will be used in the Langley 6-inch expansion tube and expansion tunnel, the effective radius is identical to the geometric nose radius $\left(\text{that is, } r_e = r_g\right)$.

Transverse cylindrical heat-transfer probes will also be used. For these probes (assuming the flow about the cylinder is two dimensional), the stagnation-point heat-transfer rate is related to that of a sphere by the expression (from ref. 56)

$$\left(\dot{q}_t\right)_{sphere} = \sqrt{2}\left(\dot{q}_t\right)_{cylinder} \tag{24}$$

For air, equation (23) takes the form

$$\dot{q}_t = 3.8798 \times 10^{-4}\sqrt{\frac{p_t}{r_g}}\left(h_t - h_w\right) \tag{25}$$

APPENDIX B

TRANSPORT PROPERTIES FOR HIGH-TEMPERATURE AIR

As discussed in reference 45, discrepancies in the results of theoretical stagnation-point heat-transfer studies can generally be attributed to (1) the assumptions employed to reduce the governing equations to a tractable form, (2) the mathematical technique used to solve the governing equations, and (3) the source of thermodynamic and transport properties used. Aspects (1) and (2) have been fairly well standardized. However, as pointed out in reference 45, uncertainties exist in the evaluation of transport properties of high-temperature (ionized) air and may result in appreciable uncertainty (up to 20 percent or so) in the calculated stagnation-point heating rate. (It should be noted that the findings of ref. 57 indicate a more insensitive relation between transport properties at high temperatures and calculated $\dot{q}_t$ than the findings of ref. 45.)

Cohen (ref. 39) states that as more accurate values of transport properties for real air become available, a better estimate of stagnation-point heat-transfer rate should be possible with equation (10). Cohen suggests that the coefficient and exponents appearing in his expression (eq. (10)) should be valid with these more accurate transport properties.

As shown in the recent study of reference 48, the viscosity data of Hansen for temperatures above 1500 K appear to be too low, deviating from the results of reference 48 by as much as 25 percent for temperatures to 8000 K. The viscosity results of reference 47 agree closely with those of reference 48. In reference 48, where dissociation but not ionization phenomena are considered, this discrepancy is attributed to the fact that Hansen uses simple kinetic theory and rough approximations for collision cross sections.

Because of the inexact knowledge of the transport properties of high-temperature air and the belief of Cohen that existing expressions may be valid with usage of more accurate transport properties, the viscosity results of both reference 46 and reference 47 are made available to the expressions of references 39 to 43. This permits the user of the procedures of this study to choose transport properties from reference 46 or 47 in predicting $\dot{q}_t$ (see appendix E).

APPENDIX C

CALCULATION SCHEME FOR INDIVIDUAL DATA-REDUCTION PROCEDURES

ITEST = 1

In the ITEST = 1 procedure, p_1 and V_1 are measured inputs, and a second free-stream thermodynamic quantity is determined. This is accomplished by estimating a value of ρ_1 from equation (5), since p_t is also a measured input. This value of $\tilde{\rho}_1$ is believed to be within approximately ±3.5 percent of the actual value. Then p_1 and $\tilde{\rho}_1$ are used as inputs to SAVE (2) to obtain the corresponding free-stream thermodynamic quantities.

With known values of p_1 and V_1 and relatively accurate values of ρ_1 and h_1, the DIRECT iterative procedure is performed. The calculated p_t obtained from DIRECT is compared with the measured p_t and if not within TOLPT, h_1 is adjusted by using the relation

$$h_1 = \frac{(h_1)_{prev}(p_t)_{c,prev}}{(p_t)_m} \tag{26}$$

This new value of h_1 is used, in conjunction with p_1, as input in SEARCH (1). The corresponding value of ρ_1 obtained from SEARCH (1) is used in DIRECT. (Note that $\tilde{\rho}_1$ from eq. (5) was used only to obtain a relatively accurate first estimate of h_1 and is not involved in the final phase of upgrading h_1.) The $(p_t)_c$ from DIRECT is again compared with $(p_t)_m$. This procedure of varying h_1 according to equation (26) is continued until $(p_t)_c$ is within TOLPT of $(p_t)_m$.

Additional free-stream parameters of interest are a_1, s_1/R, T_1, Z_1, Z_1^*, and $\gamma_{E,1}$. These parameters are all included on the AEDC tape and thus are available from SEARCH (1) for the final value of h_1 and the known p_1. Other free-stream parameters of interest are Mach number, coefficient of viscosity, and Reynolds number. The Mach number is found by dividing V_1 by a_1. For $T_1 \leqq 1500$ K, the coefficient of viscosity μ is obtained from Sutherland's expression (eq. (12)), whereas for $T_1 > 1500$ K, μ is obtained from interpolation of the results of reference 47. The unit Reynolds number is found by dividing the product $\rho_1 V_1$ by μ_1.

ITEST = 2

In the ITEST = 2 procedure, the only known free-stream flow quantity is V_1 and the known postshock conditions are p_t and $\dot{q}_t$.

Since the procedure ITEST = 5 (to be discussed subsequently) was the first to be programed for computer usage, it was used to calculate $\dot{q}_t$ from the theoretical expressions of references 39 to 43 and the empirical expression of reference 44. (See appendix A.) The five theoretical predictions, the average of these predictions, and the empirical prediction of Zoby were compared. (See fig. 2.) This comparison led to the adoption of the empirical relation of Zoby (eq. (25)) for $T_t \geqq 4500$ K. For $T_t < 4500$ K, the theoretical expression of reference 41 (eq. (17)) was adopted, with $N_{Le} = 1$ and with μ_t obtained from Sutherland's viscosity expression (eq. (12)) for $T_t \leqq 1500$ K and from interpolation of the results of reference 47 for $1500 \text{ K} < T_t < 4500$ K.

The calculation scheme for ITEST = 2 begins by determining h_t from equation (25), with p_t, $\dot{q}_t$, and r_g as measured inputs and h_w obtained as discussed in appendix A. Then h_t and p_t are used as inputs to SEARCH (1) to obtain the postshock stagnation conditions.

If $T_t \geqq 4500$ K, these stagnation conditions from SEARCH (1) are assumed to be the correct values. If $T_t < 4500$ K, the relation of reference 41 (eq. (17)) is used to obtain a value of h_t, as will be discussed subsequently. The postshock stagnation conditions that have been found and the known value of V_1 are used to obtain a value of h_1 from equation (4). An estimate of ρ_1 is obtained from equation (5) and used in conjunction with h_1 as input to SEARCH (3) in order to obtain the corresponding free-stream conditions. The DIRECT iterative procedure is used to determine the postshock static conditions and a value of $(p_t)_c$. If this $(p_t)_c$ is not within the prescribed tolerance (TOLPT) of the measured p_t, the free-stream static pressure is adjusted according to

$$p_1 = \frac{(p_1)_{prev}(p_t)_m}{(p_t)_{c,prev}} \tag{27}$$

This value of p_1 and the previously determined h_1 are used with SEARCH (1) to obtain upgraded values of free-stream flow quantities, which are then used in DIRECT. This iterative procedure, based on equation (27), is continued until the desired agreement between $(p_t)_m$ and $(p_t)_c$ is obtained. Additional free-stream and postshock conditions of interest are determined as for ITEST = 1.

For the case where $T_t < 4500$ K, initial estimates of h_t and ρ_t are obtained by using the h_t value from equation (25) and the measured p_t as inputs to SEARCH (1) to obtain ρ_t. Then μ_t is obtained from equation (12) for $T_t \leqq 1500$ K and from the results of reference 47 for $1500\ \mathrm{K} < T_t < 4500\ \mathrm{K}$. The μ_w, ρ_w, and h_w values are found from equations (12), (13), and (14), respectively. The value of p_1 is initially set at zero in equation (15). Since in most instances $p_t \gg p_1$ (for example, $p_t > 10p_1$ for $M_1 > 2.75$ in ideal air), neglecting p_1 in equation (15) will not result in an appreciable error. (The term $p_t - p_1$ appears to the 0.25 power in eq. (17).) The calculated $\dot{q}_t$ from equation (17) is compared with the measured $\dot{q}_t$. If not within the desired tolerance, h_t is varied according to the relation

$$h_t = \frac{\left(h_t - h_w\right)_{prev}\left(\dot{q}_t\right)_m}{\left(\dot{q}_t\right)_c} + h_w \tag{28}$$

and the procedure is repeated. After h_t is obtained, the free-stream conditions are determined as discussed previously. A value of β is calculated with p_1 included and compared with the value of β when $p_1 = 0$. If these β values are not within a prescribed tolerance, the upgraded value of β is used in equation (17) and the procedure is repeated.

ITEST = 3

The measured postshock conditions for the ITEST = 3 procedure are p_t and $\dot{q}_t$. Hence the method for obtaining the postshock stagnation conditions is the same as that for ITEST = 2. The INVERSE iterative procedure is then used. In INVERSE, a value of p_2 is estimated and the corresponding postshock static conditions are obtained. The measured p_1 is used to obtain V_1 by combining equations (1) and (2) to yield

$$V_1 = \frac{p_2 - p_1}{\rho_2 V_2} + V_2 \tag{29}$$

Then ρ_1 is found from equation (1) and h_1 from equation (3). This h_1 and the measured p_1 are used as inputs to SEARCH (1) to obtain the corresponding free-stream conditions. If the ρ_1 value from SEARCH (1) is not within the desired tolerance (TOLRHO) of ρ_1 obtained from equation (1), p_2 is varied and the procedure repeated.

The iterative procedure on p_2 in INVERSE is as follows: An upper and a lower limit on p_2 are established as discussed previously. The upper limit is taken as the first value of p_2 (that is, $p_2{}^{\alpha} = \left(p_2\right)_{up}^{\alpha}$). A value of Δp is obtained from

$$\Delta p^{\alpha} = \frac{\left(p_2\right)_{up}^{\alpha} - \left(p_2\right)_{low}^{\alpha}}{4} \tag{30}$$

With p_2^{α}, a value of ρ_1 is obtained as discussed above. If

$$\left| 1 - \frac{(\rho_1)_{\text{eq. (1)}}}{(\rho_1)_{\text{SEARCH (1)}}} \right| \leqq \text{TOLRHO} \tag{31}$$

then the value of p_2^{α} is considered satisfactory. If the condition of equation (31) is not met, and if $(\rho_1)_{\text{SEARCH (1)}} > (\rho_1)_{\text{eq. (1)}}$, then

$$p_2^{\alpha+1} = p_2^{\alpha} - \Delta p^{\alpha} \tag{32}$$

but if $(\rho_1)_{\text{SEARCH (1)}} < (\rho_1)_{\text{eq. (1)}}$, the limits of p_2 are varied according to

$$(p_2)_{\text{low}}^{\alpha+1} = p_2^{\alpha} \tag{33a}$$

$$(p_2)_{\text{up}}^{\alpha+1} = p_2^{\alpha} + \Delta p^{\alpha} \tag{33b}$$

A new value of Δp is calculated $\left(\Delta p^{\alpha+1}\right)$, and $p_2^{\alpha+1}$ becomes

$$p_2^{\alpha+1} = (p_2)_{\text{up}}^{\alpha+1} - \Delta p^{\alpha+1} \tag{34}$$

The procedure is repeated with $p_2^{\alpha+1}$ and new values of ρ_1 are obtained. This iterative procedure is continued until the ρ_1 value obtained from equation (1) is within the desired accuracy of the ρ_1 value from SEARCH (1).

In the course of this iteration, it is possible that values of h_1 less than the minimum value of h_1 on the AEDC tape (or even negative values of h_1) may occur. In this case, the p_2 for which this occurred is varied according to equation (34) and the calculation scheme is continued.

ITEST = 4

The measured inputs for the ITEST = 4 procedure are p_1, V_1, and $\dot{q}_t$. The first consideration is to obtain an estimate of h_1 or ρ_1. Combining equations (4) and (25) and solving for p_t gives

$$p_t = \frac{r_g\left(2.57745 \times 10^3 \dot{q}_t\right)^2}{\left(h_1 - h_w + \frac{1}{2} V_1^2\right)^2} \tag{35}$$

Assuming $h_1 - h_w << \frac{1}{2} V_1^2$ and introducing equation (5) into equation (35) yields

$$\tilde{\rho}_1 = \frac{2.6841 \times 10^7 r_g \dot{q}_t^2}{V_1^6} \tag{36}$$

(An expression for h_1 in terms of the measured inputs was obtained by combining equations (4), (5), and (25). However, this expression proved to be unsatisfactory since relatively small errors in $\dot{q}_t$ and V_1 often resulted in $h_1 < 0$.) The uncertainty in $\tilde{\rho}_1$ is dictated by the validity of the assumption $h_1 - h_w << \frac{1}{2} V_1^2$, by whether $T_t \geqq 4500$ K (region where eq. (25) is considered valid), and by the relatively small uncertainty in C of equation (5). Calculations for typical expansion tube tests, where $h_1 - h_w << \frac{1}{2} V_1^2$ and $T_t \geqq 4500$ K showed that $\tilde{\rho}_1$ was approximately 2 to 5 percent greater than the actual value. However, calculations for a few shock tube cases, where $T_t \geqq 4500$ K but $h_1 - h_w$ was not much less than $\frac{1}{2} V_1^2$, showed that $\tilde{\rho}_1$ was much smaller than the actual value. For this procedure, limits on ρ_1 that should prove to be valid for nearly all cases are

$$\left(\rho_1\right)_{up} = 2.05\tilde{\rho}_1$$

$$\left(\rho_1\right)_{low} = 0.20\tilde{\rho}_1$$

For Mach numbers greater than 8 or so, these limits may be refined to

$$\left(\rho_1\right)_{up} = 1.05\tilde{\rho}_1$$

$$\left(\rho_1\right)_{low} = 0.85\tilde{\rho}_1$$

Again, the user is urged to adjust these limits so as to minimize the range of iteration on ρ_1 for his particular problem.

The $\tilde{\rho}_1$ and measured p_1 are used as inputs to SEARCH (2) to obtain the corresponding free-stream conditions. With estimates of ρ_1 and h_1 and known values of p_1 and V_1, the DIRECT iterative procedure is used to find postshock flow conditions, including $\dot{q}_t$. This calculated $\dot{q}_t$ is compared with the measured $\dot{q}_t$, and if not within the desired tolerance (TOLQT), the value of ρ_1 is varied and the procedure repeated.

The iterative procedure on ρ_1 for the case where $M_1 > 8$ is as follows: When the upper and lower limits on ρ_1 have been established, the initial value of ρ_1 is taken to be $0.95\tilde{\rho}_1$ $\left(\text{that is, } \rho_1^{\ \alpha} = 0.95\tilde{\rho}_1\right)$. A value of $\Delta\rho^\alpha$ is obtained from

$$\Delta\rho^\alpha = \frac{\left(\rho_1\right)_{up}^{\alpha} - \left(\rho_1\right)_{low}^{\alpha}}{4} \tag{37}$$

With $\rho_1^{\ \alpha}$ and p_1, the corresponding free-stream conditions are obtained from SEARCH (2), and DIRECT is used to find the postshock conditions. A value of $\dot{q}_t$ is calculated. If

$$\left| 1 - \frac{\left(\dot{q}_t\right)_m}{\left(\dot{q}_t\right)_c} \right| \leqq \text{TOLQT} \tag{38}$$

then the value of $\rho_1^{\ \alpha}$ is considered satisfactory. If the condition of equation (38) is not met, and if $\left(q_t\right)_c > \left(q_t\right)_m$, then

$$\rho_1^{\ \alpha+1} = \rho_1^{\ \alpha} - \Delta\rho^\alpha \tag{39}$$

but if $\left(q_t\right)_c < \left(q_t\right)_m$, the limits of ρ_1 become

$$\left(\rho_1\right)_{up}^{\alpha+1} = \rho_1^{\ \alpha} + \Delta\rho^\alpha \tag{40a}$$

$$\left(\rho_1\right)_{low}^{\alpha+1} = \rho_1^{\ \alpha} \tag{40b}$$

A new value of $\Delta\rho$ is calculated $\left(\Delta\rho^{\alpha+1}\right)$ and $\rho_1^{\ \alpha+1}$ becomes

$$\rho_1^{\alpha+1} = \left(\rho_1\right)_{up}^{\alpha+1} - \Delta\rho^{\alpha+1} \tag{41}$$

This iterative procedure is continued until the condition of equation (38) is satisfied.

ITEST = 5

The inputs for the ITEST = 5 procedure are p_1, ρ_1, and V_1. The values of p_1 and ρ_1 are used as inputs to SEARCH (2) to obtain the corresponding free-stream conditions. Then the postshock conditions are obtained from DIRECT.

ITEST = 6

In the ITEST = 6 procedure, the measured inputs are p_1, ρ_1, and p_t. The free-stream thermodynamic conditions are obtained as for ITEST = 5. The value of V_1 is estimated from equation (5) and the DIRECT iterative procedure is employed. The calculated p_t from DIRECT is compared with the measured p_t and, if within the desired tolerance (TOLPT), the estimated V_1 is considered satisfactory. If not within the desired tolerance, the V_1 value is adjusted by using the formula

$$V_1 = \left(V_1\right)_{prev}\sqrt{\frac{\left(p_t\right)_m}{\left(p_t\right)_{c,prev}}} \tag{42}$$

This new value of V_1 is used in DIRECT. Then V_1 is upgraded according to equation (42) until $\left(p_t\right)_c$ is within TOLPT of $\left(p_t\right)_m$.

ITEST = 7

The measured inputs for the ITEST = 7 procedure are ρ_1, p_t, and ρ_t. The postshock stagnation conditions are obtained by using p_t and ρ_t as inputs to SEARCH (2). The INVERSE iterative procedure is employed. When p_2 has been estimated and the corresponding postshock static conditions have been determined, V_1 is obtained from equation (1), p_1 from equation (2), and h_1 from equation (3). Then p_1 and h_1 are used as inputs to SEARCH (1), and the corresponding ρ_1 from SEARCH (1) is compared with the measured ρ_1. If not within the desired tolerance (TOLRHO), p_2 is varied and the procedure repeated. The variation of p_2 is the same as in the ITEST = 3 procedure, with the condition $\left(\rho_1\right)_c < \left(\rho_1\right)_m$ replacing the condition $\left(\rho_1\right)_{SEARCH\ (1)} < \left(\rho_1\right)_{eq.\ (1)}$ of ITEST = 3. In the course of this iteration on p_2, it is possible that negative values of p_1 and h_1 may occur. If so, then the limits on p_2

are adjusted according to equation (32), a new value of p_2 is found, and the calculation scheme is continued.

ITEST = 8

The measured inputs for the ITEST = 8 procedure are p_1, p_t, and ρ_t. The postshock stagnation conditions are determined as for ITEST = 7. The INVERSE iterative procedure is employed in the same way as in ITEST = 3.

ITEST = 9

In the ITEST = 9 procedure, the measured inputs are V_1, p_t, and ρ_t. The postshock stagnation conditions are determined as for ITEST = 7. Then h_1 is obtained from equation (4) and ρ_1 is estimated from equation (5). The corresponding free-stream conditions are obtained from SEARCH (3). The DIRECT iterative procedure is employed and p_1 is upgraded as in ITEST = 2 (that is, according to eq. (27)) until $(p_t)_c$ is within the desired tolerance of $(p_t)_m$.

APPENDIX D

LISTING OF COMPUTER PROGRAM FOR DATA-REDUCTION PROCEDURES WITH SAMPLE DATA PRINTOUT

The data-reduction procedures for determining free-stream and post-normal-shock flow conditions for real air in thermochemical equilibrium are incorporated into a single computer program. This program is written in FORTRAN IV language for a Control Data 6600 series computer. Minimum machine requirements are 130 000 octal locations of core storage. A listing of this program, including subroutines and comments, is reproduced on the following pages.

```
JOB,1,1000,130000,6000.          A3238    RGK143                       1247A        CENT
USER.MILLER, CHARLES G  III            000605575N 34540
RUN(S),
REQUEST,TAPE8,HY.        705042,ROL,CGM,
REWIND(TAPE8),
SETINDF. ,
LGO.    ,
UNLOAD(TAPE8),
EXIT.,
UNLOAD(TAPE8),
- ,
      PROGRAM MILLER(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE8)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      DIMENSION RESULT(2)
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
      NAMELIST /INP/ P5M,U5M,RHO5M,PT5M,QT5M,RHOT5M,ITEST,RN,TWE,TAU,TOL
     1PT,TOLQT,TOLRHO,YOS,QDO,SPH,TWALL,ETA,RUN,SAV
      CALL DAYTIM (RESULT)
1     P5M=PT5M=RHO5M=RHOT5M=QT5M=U5M=0.0
      TOLPT=TOLRHO=.001
      TOLQT=.005
      SPH=TWALL=0.
      YOS=QDO=SAV=1.
      TWE=300.
      RN=.01
      ETA=2.045E+8
      TAU=.0001
      READ (5,INP)
      IF (ENDFILE 5) 16,2
2     ICODE=0
      NV=9
      IT=8
      R=287.0245
      MM=0
      ISP=1
      NCO=0
      PRINT 17, RESULT(1)
      PRINT 18
```

```
      PRINT 19
      PRINT 20
      PRINT 21
      PRINT 22, RUN,P5M,U5M,PT5M,QT5M,RHO5M,RHOT5M,TAU
      GO TO (3,4,4,7,8,8,11,11,11), ITEST
C
C     ITEST 1 CONTAINED IN MAIN PROGRAM
C
3     PT5=PT5M
      P5=P5M
      U5=U5M
      R5EST=PT5/(.965*U5**2)
      RHO5=R5EST
C
C         IF SAV=0, THERMODYNAMIC PROPERTIES OBTAINED FROM AEDC TAPE
C         IF SAV=1, THERMODYNAMIC PROPERTIES COMPUTED FROM CURVE-FIT
C
      CALL SAVE (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,2)
      CALL DIRECT (PT5M)
      GO TO 15
4     IF (ITEST.EQ.3) GO TO 5
      XX=U5M
      GO TO 6
5     XX=P5M
6     CALL PROC2 (PT5M,QT5M,XX)
      GO TO 15
7     CALL PROC4 (P5M,U5M,QT5M)
      GO TO 15
8     IF (ITEST.EQ.5) GO TO 9
      YY=PT5M
      GO TO 10
9     YY=U5M
10    CALL PROC5 (RHO5M,P5M,YY)
      GO TO 15
11    IF (ITEST.EQ.7) GO TO 12
      IF (ITEST.EQ.8) GO TO 13
      YY=U5M
      GO TO 14
12    YY=RHO5M
      GO TO 14
13    YY=P5M
14    CALL PROC7 (PT5M,RHOT5M,YY)
15    IF (ICODE.EQ.1) GO TO 1
      M5=U5/A5
```

```
C
C     OBTAIN MU5(USING RESULTS OF YOS) AND RE5 FROM QDOT
C
      CALL QDOT (0.,0.,0.)
C
C     OBTAIN PREDICTED QT5 FROM QDOT IF INPUT QDO IS NOT 0
C
      CALL QDOT (0.,0.,1.)
      PRINT 23
      PRINT 24
      PRINT 25, P5,RHO5,T5,H5,S5R,Z5,GAME5,A5,U5,M5,RE5
      PRINT 26
      PRINT 24
      PRINT 25, P5S,RHO5S,T5S,H5S,S5SR,Z5S,GAME5S,A5S,U5S,M5S,RE5S
      PRINT 27
      PRINT 28
      PRINT 29, PT5,RHOT5,TT5,HT5,ST5R,ZT5,GAMET5,AT5
      IF (QDO.EQ.0.) GO TO 1
      PRINT 30
      PRINT 31
      PRINT 32, QT5CO,QT5HOS,QT5FR,QT5PT,QT5DE,QT5ZO,RN
      GO TO 1
16    STOP
C
17    FORMAT (1H1,A10//)
18    FORMAT (44H    REAL-AIR DATA REDUCTION PROGRAM OF MILLER)
19    FORMAT (/53H   ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012)
20    FORMAT (///17H   MEASURED INPUTS)
21    FORMAT (/79H     RUN            P1             V1             PT             QT          R
     1HO1            RHOT           TIME)
22    FORMAT (8E10.3)
23    FORMAT (///24H   FREE-STREAM CONDITIONS)
24    FORMAT (/107H     P             RHO            T              H              S/R
     1 Z            GAME           A              V              M              NRE)
25    FORMAT (11E10.3)
26    FORMAT (///39H   STATIC CONDITIONS BEHIND NORMAL SHOCK)
27    FORMAT (///43H   STAGNATION CONDITIONS BEHIND NORMAL SHOCK)
28    FORMAT (/75H     P             RHO            T              H              S/R
     1Z             GAME           A)
29    FORMAT (8E10.3)
30    FORMAT (///44H   STAGNATION POINT HEAT TRANSFER PREDICTIONS)
31    FORMAT (/65H   QTCO           QTHOS          QTFR           QTPT           QTDE          Q
     1TZO           RN)
32    FORMAT (7E10.3)
```

```
      END
      SUBROUTINE PROC2 (PT5M,QT5M,XX)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
C
C     FOR ITEST=2, XX=U5M AND USE DIRECT
C     FOR ITEST=3, XX=P5M AND USE INVERSE
C
      PT5=PT5M
      QT5=QT5M
C
C     TWALL MUST BE 0(TW=TWE) OR BE 1
C
C     FINITE VALUE OF ETA(=CP*RHO*K) MUST BE FURNISHED
      TW=TWE+1.7725*QT5*TWALL*SQRT(TAU/ETA)
      HW=1.0046E+3*TW
      HT5=2.57745E+3*QT5*SQRT(RN/PT5)*2.**(SPH/2.)+HW
      IF (ITEST.EQ.3) GO TO 1
C
C     FOR ITEST=2, ESTIMATE INITIAL BO BY SETTING P5=0
C
      P5=0.
      GO TO 2
1     P5M=XX
      P5=P5M
2     IF (SAV.EQ.1.) GO TO 3
      CALL SEARCH (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,ISP,1)
      GO TO 4
3     CALL SAVE (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,3)
C
C     IF TT5 .GE. 4500K, USE ZOBY RELATION TO OBTAIN HT5
C
4     IF (TT5.GE.4500.) GO TO 6
C
C     IF TT5 .LT. 4500K, USE FAY-RIDDELL WITH MUT5 FROM YOS
C
5     CALL QDOT (QT5M,1.,1.)
6     IF (ITEST.EQ.3) GO TO 10
```

```
      U5M=XX                                                            B  44
      U5=U5M                                                            B  45
      H5=HT5-.5*U5**2                                                   B  46
      IF (H5.GT.1.E+5) GO TO 7                                          B  47
      PRINT 12                                                          B  48
      ICODE=1                                                           B  49
      GO TO 11                                                          B  50
7     R5EST=PT5/(.965*U5**2)                                            B  51
      RHO5=R5EST                                                        B  52
      IF (SAV.EQ.1.) GO TO 8                                            B  53
      CALL SEARCH (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ISP,3)          B  54
      GO TO 9                                                           B  55
8     CALL SAVE (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,4)                       B  56
9     CALL DIRECT (PT5M)                                                B  57
C                                                                       B  58
C     BOCOM IS COMPARISON OF INITIAL BO TO UPGRADED BO(P5 .NE. 0)       B  59
C                                                                       B  60
      BOCOM=SQRT(PT5/(PT5-P5))                                          B  61
C                                                                       B  62
C     IF INITIAL BO NOT WITHIN 4 PERCENT OF UPGRADED BO, REPEAT         B  63
C                                                                       B  64
      IF (BOCOM.LE.1.02) GO TO 11                                       B  65
      GO TO 5                                                           B  66
10    CALL INVERSE (XX)                                                 B  67
11    RETURN                                                            B  68
C                                                                       B  69
12    FORMAT (46H H1 IS LESS THAN MINIMUM VALUE ON TAPE,ITEST=2)        B  70
      END                                                               B  71-
      SUBROUTINE PROC4 (P5M,U5M,QT5M)                                   C   1
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE             C   2
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5       C   3
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV                  C   4
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S                        C   5
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT     C   6
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR    C   7
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST                 C   8
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM                              C   9
      NN=0                                                              C  10
      QT5=QT5M                                                          C  11
      P5=P5M                                                            C  12
      U5=U5M                                                            C  13
C                                                                       C  14
C     TWALL MUST BE 0(TW=TWE) OR BE 1                                   C  15
C                                                                       C  16
```

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C     FINITE VALUE OF ETA(=CP*RHO*K) MUST BE FURNISHED
      TW=TWE+1.7725*QT5*TWALL*SQRT(TAU/ETA)
      HW=1.0046E+3*TW
      R5EST=2.6841E+7*RN*QT5M**2/U5M**6
      RHOUP=2.05*R5EST
      RHOLOW=.20*R5EST
C
C     USER CAUTIONED ON THESE LIMITS OF RHO5(RHO1)
C     THESE LIMITS SHOULD BE VALID FOR NEARLY ALL CASES
C     TO MINIMIZE COMPUTER TIME, SHOULD REFINE LIMITS
C              FOR M5 GREATER THAN 10, LET RHOLOW BE .85*R5EST
C              AND RHOUP BE 1.05*R5EST
C
      RHO5=1.45*R5EST
1     DELRHO=(RHOUP-RHOLOW)/4.
      IF (NN.EQ.0) GO TO 2
      RHO5=RHOUP-DELRHO
2     IF (SAV.EQ.1.) GO TO 3
      CALL SEARCH (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ISP,2)
      GO TO 4
3     CALL SAVE (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,2)
4     PT5=.965*RHO5*U5**2
      PT5M=PT5
      CALL DIRECT (PT5M)
      IF (TT5.LT.4500.) GO TO 6
      QT5ZO=3.8798E-4*SQRT(PT5/RN)*(HT5-HW)/2.**(SPH/2.)
C
C     TOLQT REPRESENTS TOLERANCE OF ITERATION ON QT5
C
      IF (ABS(1.-QT5M/QT5ZO).LE.TOLQT) GO TO 8
      IF (NN.EQ.15) GO TO 7
      NN=NN+1
      IF (QT5ZO.LT.QT5M) GO TO 5
      RHO5=RHO5-DELRHO
      GO TO 2
5     RHOLOW=RHO5
      RHOUP=RHO5+DELRHO
      GO TO 1
6     CALL QDOT (QT5M,1.,1.)
C
C     TOLQT REPRESENTS TOLERANCE OF ITERATION ON QT5
C
      IF (ABS(1.-QT5M/QT5FR).LE.TOLQT) GO TO 8
      IF (NN.EQ.15) GO TO 7
```

```
      NN=NN+1
      IF (QT5FR.LT.QT5M) GO TO 5
      RHO5=RHO5-DELRHO
      GO TO 2
    7 PRINT 9
      PRINT 10
      ICODE=1
    8 RETURN
C
    9 FORMAT (50H ITERATIONS ON RHO5 EXCEED LIMIT OF 15 FOR ITEST=4)
   10 FORMAT (21H CHECK LIMITS ON RHO5)
      END
      SUBROUTINE PROC5 (RHO5M,P5M,YY)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
C
C     FOR ITEST=5, YY=U5M AND USE DIRECT
C     FOR ITEST=6, YY=PT5M AND USE DIRECT
C
      RHO5=RHO5M
      P5=P5M
      IF (ITEST.EQ.5) GO TO 1
      PT5M=YY
      PT5=PT5M
      GO TO 2
    1 U5M=YY
      U5=U5M
    2 IF (SAV.EQ.1.) GO TO 3
      CALL SEARCH (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ISP,2)
      GO TO 4
    3 CALL SAVE (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,2)
    4 IF (ITEST.EQ.5) GO TO 5
C
C     FOR ITEST=6, MUST ESTIMATE U5 FOR DIRECT
C     UPGRADING OF U5 PERFORMED IN DIRECT
C
      U5=SQRT(PT5/(.965*RHO5))
      GO TO 6
```

```
C
C     FOR ITEST=5, MUST ESTIMATE PT5M FOR USE IN DIRECT
C
5     PT5=.965*RHO5*U5**2
      PT5M=PT5
6     CALL DIRECT (PT5M)
      RETURN
      END
      SUBROUTINE PROC7 (PT5M,RHOT5M,YY)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
C
C     FOR ITEST=7, YY=RHO5M AND USE INVERSE
C     FOR ITEST=8, YY=P5M AND USE INVERSE
C     FOR ITEST=9, YY=U5M AND USE DIRECT
C
      PT5=PT5M
      RHOT5=RHOT5M
      IF (SAV.EQ.1.) GO TO 1
      CALL SEARCH (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,ISP,2)
      GO TO 2
1     CALL SAVE (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,2)
C
C     AT THIS POINT, KNOW STAGNATION CONDITIONS EXACTLY
C
2     IF (ITEST.EQ.9) GO TO 3
      CALL INVERSE (YY)
      GO TO 7
3     U5M=YY
      U5=U5M
      H5=HT5-.5*U5**2
      IF (H5.GT.1.E+5) GO TO 4
      PRINT 8
      ICODE=1
      GO TO 7
4     R5EST=PT5/(.965*U5**2)
      RHO5=R5EST
      IF (SAV.EQ.1.) GO TO 5
```

```
      CALL SEARCH (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ISP,3)
      GO TO 6
 5    CALL SAVE (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,4)
 6    CALL DIRECT (PT5M)
 7    RETURN
C
 8    FORMAT (50H H1 IS LESS THAN MINIMUM VALUE ON TAPE FOR ITEST=9)
      END
      SUBROUTINE DIRECT (PT5M)
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), NP(4)
      DIMENSION TABP(3), TABH(3)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      COMMON ICOUNT,IMET(2),NP,ABAR,ME,MF
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
      IMET(1)=IMET(2)=0
C
C     DIRECT PERFORMS NORMAL SHOCK CROSSING, PRE-TO-POST
C
 1    BSNS=RHO5*U5
      CSNS=P5+BSNS*U5
      DSNS=H5+.5*U5**2
      HT5=H5+.5*U5**2
      CALL SAVE (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,3)
      RHO5S=.955*RHOT5
 2    U5S=BSNS/RHO5S
      P5S=CSNS-BSNS*U5S
      H5S=DSNS-.5*U5S**2
      IF (SAV.EQ.1.) GO TO 3
      CALL SEARCH (P5S,RNEW,H5S,S5SR,T5S,A5S,Z5S,GAME5S,ZSTAR5S,ISP,1)
      GO TO 4
 3    CALL SAVE (P5S,RNEW,H5S,S5SR,T5S,A5S,Z5S,GAME5S,3)
 4    IF (ABS(1.-RHO5S/RNEW).LE..001) GO TO 5
      RHO5S=RNEW
      GO TO 2
 5    RHO5S=RNEW
      M5S=U5S/A5S
      HT5R=HT5/R
      IF (SAV.EQ.1.) GO TO 6
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```
      XX=S5SR
      Z(4)=ALOG10(HT5R)
      CALL SLOW (XX,Z,4,3,IT,NV,NERR,Y,X)
      PT5=(10.**Z(3))*1.01325E+5
      GO TO 8
6     PT5=P5S*(1.+((GAME5S-1.)/2.)*M5S**2)**(GAME5S/(GAME5S-1.))
      TABP(1)=.95*PT5
      TABP(2)=PT5
      TABP(3)=1.05*PT5
      DO 7 I=1,3
      PT5=TABP(I)
      CALL SAVE (PT5,RHOT5,HT5A,S5SR,TT5,AT5,ZT5,GAMET5,1)
      TABH(I)=HT5A
7     CONTINUE
      CALL FTLUP (HT5,PT5,2,3,TABH,TABP)
      CALL SAVE (PT5,RHOT5,HT5,S5SR,TT5,AT5,ZT5,GAMET5,1)
8     IF (ITEST.EQ.4.OR.ITEST.EQ.5) GO TO 13
C
C     TOLPT REPRESENTS TOLERANCE OF ITERATION ON PT5
C
      IF (ABS(1.-PT5M/PT5).LE.TOLPT) GO TO 13
      IF (ITEST.EQ.2.OR.ITEST.EQ.9) GO TO 10
      IF (ITEST.EQ.1) GO TO 9
      U5=U5*SQRT(PT5M/PT5)
      GO TO 1
9     H5=H5*PT5/PT5M
      GO TO 11
10    P5=P5*PT5M/PT5
11    IF (SAV.EQ.1.) GO TO 12
      CALL SEARCH (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ISP,1)
      GO TO 1
12    CALL SAVE (P5,RHO5,H5,S5R,T5,A5,Z5,GAME5,3)
      GO TO 1
13    IF (SAV.EQ.1.) GO TO 14
      CALL SEARCH (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,ISP,1)
      GO TO 15
14    CALL SAVE (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,3)
15    RETURN
      END
      SUBROUTINE INVERSE (ZZ)
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), NP(4)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
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      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      COMMON ICOUNT,IMET(2),NP,ABAR,ME,MF
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
      IMET(1)=IMET(2)=0
C
C     INVERSE PERFORMS NORMAL SHOCK CROSSING,  POST-TO-PRE
C
      XX=ST5R
      MM=0
      PLOW=.850*PT5
      PUP=.970*PT5
C
C     USER CAUTIONED ON THESE LIMITS OF P5S(P2)
C     IF M5 LESS THAN 3, MAY HAVE TO LOWER PLOW
C     TO MINIMIZE COMPUTER TIME,SHOULD ALSO LOWER PUP
C
      P5S=PUP
    1 DELP=(PUP-PLOW)/4.
      IF (MM.EQ.0) GO TO 2
      P5S=PUP-DELP
    2 IF (SAV.EQ.1.) GO TO 3
      Z(3)=ALOG10(P5S/1.01325E+5)
      CALL SLOW (XX,Z,3,4,IT,NV,NERR,Y,X)
      CALL SLOW (XX,Z,3,2,IT,NV,NERR,Y,X)
      H5S=(10.**Z(4))*R
      RHO5S=(10.**Z(2))*1.2914889
      GO TO 4
    3 CALL SAVE (P5S,RHO5S,H5S,ST5R,T5S,A5S,Z5S,GAME5S,1)
    4 U5S=SQRT(2.*(HT5-H5S))
      IF (MM.EQ.35) GO TO 13
      MM=MM+1
      IF (ITEST.EQ.3.OR.ITEST.EQ.8) GO TO 9
      RHO5M=ZZ
      RHO5=RHO5M
      U5=RHO5S*U5S/RHO5
      P5=P5S+RHO5S*U5S**2-RHO5*U5**2
      IF (P5.LT..1) GO TO 8
      H5=HT5-.5*U5**2
      IF (H5.LT.1.E+5) GO TO 8
    5 IF (SAV.EQ.1.) GO TO 6
      CALL SEARCH (P5,RHOE,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ISP,1)
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      GO TO 7
6     CALL SAVE (P5,RHOE,H5,S5R,T5,A5,Z5,GAME5,3)
C
C     TOLRHO REPRESENTS TOLERANCE OF ITERATION ON RHO5
C
7     IF (ABS(1.-RHO5/RHOE).LE.TOLRHO) GO TO 10
      IF (RHOE.LT.RHO5) GO TO 8
      P5S=P5S-DELP
      GO TO 2
8     PLOW=P5S
      PUP=P5S+DELP
      GO TO 1
9     P5M=ZZ
      P5=P5M
      U5=(P5S-P5)/(RHO5S*U5S)+U5S
      RHO5=RHO5S*U5S/U5
      H5=HT5-.5*U5**2
      IF (H5.GT.1.E+5) GO TO 5
      P5S=P5S-DELP
      GO TO 2
10    IF (SAV.EQ.1.) GO TO 11
      CALL SEARCH (P5S,RHO5S,H5S,S5SR,T5S,A5S,Z5S,GAME5S,ZSTAR5S,ISP,1)
      GO TO 12
11    CALL SAVE (P5S,RHO5S,H5S,S5SR,T5S,A5S,Z5S,GAME5S,3)
12    M5S=U5S/A5S
      GO TO 14
13    PRINT 15
      ICODE=1
14    RETURN
C
15    FORMAT (52H ITERATIONS ON P2 EXCEED LIMIT - REFINE LIMITS ON P2)
      END
      SUBROUTINE QDOT (QT5M,BIT,DIT)
      DIMENSION TABP(7), TABT(25), TABNU(175)
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), NP(4)
      DIMENSION TAPY(4), TABTY(13), TABNUY(52)
      COMMON /BLK1/ RHO5,H5,S5R,T5,A5,Z5,GAME5,ZSTAR5,ICODE
      COMMON /BLK2/ RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,PT5
      COMMON /BLK3/ TWE,TAU,TW,QT5DE,SPH,TWALL,ETA,SAV
      COMMON /BLK4/ NV,IT,R,MM,ISP,NCO,MN,GAME5S
      COMMON /BLK5/ P5,U5,M5,MU5,RE5,QT5FR,QT5HOS,QT5CO,QT5ZO,QT5PT
      COMMON /BLK6/ P5S,T5S,RHO5S,H5S,A5S,Z5S,U5S,M5S,MU5S,RE5S,S5SR
      COMMON /BLK7/ RN,TOLPT,TOLQT,TOLRHO,YOS,QDO,ITEST
      REAL M5,MU5,M5S,MU5S,MUW,MUT5,NU,LAM
```

```
C
C     TABLE OF VISCOSITY FROM HANSEN(NASA TR R-50)
C
      DATA TABP/1.01325E+7,1.01325E+6,1.01325E+5,1.01325E+4,1.01325E+3,1
     1.01325E+2,1.01325E+1/
      DATA TABT/3000.,3500.,4000.,4500.,5000.,5500.,6000.,6500.,7000.,75
     100.,8000.,8500.,9000.,9500.,10000.,10500.,11000.,11500.,12000.,125
     200.,13000.,13500.,14000.,14500.,15000./
      DATA TABNU/2*1.0,1.003,1.010,1.022,1.036,1.050,1.072,1.089,1.112,1
     1.143,1.185,1.238,1.298,1.361,1.418,1.467,1.509,1.549,1.577,1.581,1
     2.594,1.599,1.601,1.604,1.0,1.001,1.008,1.022,1.036,1.052,1.067,1.0
     390,1.124,1.175,1.238,1.307,1.368,1.418,1.468,1.496,1.501,1.511,1.5
     420,1.516,1.508,1.492,1.468,1.415,1.387,1.,1.003,1.016,1.029,1.043,
     51.060,1.090,1.139,1.208,1.283,1.342,1.386,1.425,1.438,1.445,1.448,
     61.442,1.424,1.394,1.342,1.274,1.187,1.082,.94,.828,1.,1.006,1.02,1
     7.033,1.051,1.086,1.148,1.229,1.294,1.332,1.371,1.386,1.396,1.393,1
     8.375,1.335,1.267,1.168,1.040,.881,.711,.547,.408,.268,.212,1.,1.01
     9,1.022,1.038,1.074,1.146,1.228,1.276,1.317,1.337,1.347,1.343,1.314
     $,1.251,1.143,.983,.782,.571,.387,.249,.158,.100,.067,.042,.016,1.,
     $1.01,1.024,1.055,1.128,1.209,1.257,1.286,1.303,1.307,1.28,1.207,1.
     $068,.853,.595,.361,.200,.108,.063,.036,.024,.018,.015,.013,.012,1.
     $,1.011,1.032,1.096,1.181,1.227,1.256,1.271,1.264,1.210,1.072,.826,
     $.517,.261,.118,.055,.029,.018,.012,.009,.008,.007,.007,.008,.008/
C
C     TABLE OF VISCOSITY FROM YOS(AVCO RAD-TM-63-7)
C
      DATA TAPY/1.01325E+5,3.03975E+5,1.01325E+6,3.03975E+6/
      DATA TABTY/1000.,2000.,3000.,4000.,5000.,6000.,7000.,8000.,9000.,1
     10000.,12000.,14000.,16000./
      DATA TABNUY/.418E-4,.648E-4,.858E-4,1.08E-4,1.30E-4,1.54E-4,1.86E-
     14,2.21E-4,2.46E-4,2.63E-4,2.63E-4,1.77E-4,.96E-4,.418E-4,.648E-4,.
     2857E-4,1.07E-4,1.30E-4,1.52E-4,1.80E-4,2.14E-4,2.45E-4,2.66E-4,2.8
     35E-4,2.34E-4,1.53E-4,.418E-4,.648E-4,.857E-4,1.07E-4,1.30E-4,1.51E
     4-4,1.76E-4,2.06E-4,2.4E-4,2.67E-4,3.00E-4,2.82E-4,2.24E-4,.418E-4,
     5.648E-4,.856E-4,1.06E-4,1.27E-4,1.50E-4,1.73E-4,2.00E-4,2.32E-4,2.
     663E-4,3.06E-4,3.10E-4,2.66E-4/
      MM=0
C
C     QDOT CONSISTS OF 3 SECTIONS
C
      IF (DIT.EQ.1.) GO TO 5
C
C     (1) PREDICTING MU5(USING YOS RESULTS) AND RE5
C
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      IF (T5.LE.1500.) GO TO 1
      CALL DISCOT (T5,P5,TABTY,TABNUY,TAPY,11,52,4,MU5)
      GO TO 2
    1 MU5=1.462E-6*SQRT(T5)/(1.+112./T5)
    2 RE5=RHO5*U5/MU5
      IF (T5S.LE.1500.) GO TO 3
      CALL DISCOT (T5S,P5S,TABTY,TABNUY,TAPY,11,52,4,MU5S)
      GO TO 4
    3 MU5S=1.462E-6*SQRT(T5S)/(1.+112./T5S)
    4 RE5S=RHO5*U5/MU5S
      GO TO 20
C
C     (2) PREDICTING QT5 WITH HANSEN OR YOS RESULTS FOR MUT5
C
    5 PR=.71
      NN=0
      TW=TWE
    6 HW=1.0046E+3*TW
      RHOW=3.48398E-3*PT5/TW
      MUW=1.462E-6*SQRT(TW)/(1.+112./TW)
      BO=(1./RN)*SQRT(2.*(PT5-P5)/RHOT5)
      IF (BIT.EQ.1.) GO TO 16
C
C     IF QDO=0, VARIOUS QT5 WILL NOT BE COMPUTED
C
      IF (QDO.EQ.0.) GO TO 20
      IF (TT5.GT.1500.) GO TO 7
      MUT5=1.462E-6*SQRT(TT5)/(1.+112./TT5)
      GO TO 9
C
C     IF YOS=0, USE HANSENS RESULTS FOR MUT5
C     IF YOS=1, USE YOS RESULTS FOR MUT5
C
    7 IF (YOS.EQ.0.) GO TO 8
      CALL DISCOT (TT5,PT5,TABTY,TABNUY,TAPY,11,52,4,MUT5)
      GO TO 9
    8 CALL DISCOT (TT5,PT5,TABT,TABNU,TABP,11,175,7,NU)
      MUT5=1.462E-6*SQRT(TT5)/(1.+112./TT5)
      MUT5=MUT5*NU
    9 QT5HOS=1.1672*(SQRT(BO*RHOW*MUW*TW**.4))*(U5**1.69)*(1.-HW/HT5)/2.
     1**(SPH/2.)
      QT5FR=.760*((RHOW*MUW)**.1)*((RHOT5*MUT5)**.4)*(HT5-HW)*SQRT(BO)/(
     1(PR**0.6)*2.**(SPH/2.))
      IF (U5.LE.8.84E+3) 10,11
```

```
10    EPS=0.0
      GO TO 12
11    EPS=1.
12    QT5C0=.7670*((RHOW*MUW)**.07)*((RHOT5*MUT5)**.43)*(HT5-HW)*SQRT(BO
     1)*(1.+.075*EPS*(HT5/1.9686E+7-2.)**2)/((PR**0.6)*2.**(SPH/2.))
      QT5Z0=3.8798E-4*SQRT(PT5/RN)*(HT5-HW)/2.**(SPH/2.)
      IF (U5.LE.9.906E+3) 13,14
13    LAM=1.
      GO TO 15
14    LAM=U5/9.906E+3
15    QT5PT=0.9000*((RHOW*MUW)**.07)*((RHOT5*MUT5)**.43)*(HT5-HW)*SQRT(B
     1O)*LAM/((PR**0.75)*2.**(SPH/2.))
      QT5DF=.62*((RHOW*MUW)**.1624)*((RHOT5*MUT5)**.3376)*(HT5-HW)*SQRT(
     1BO)/(PR*2.**(SPH/2.))
      IF (TWALL.EQ.0.) GO TO 20
      IF (NN.EQ.2) GO TO 20
      NN=NN+1
      QT5=QT5Z0
      TW=TWE+1.7725*QT5*TWALL*SQRT(TAU/ETA)
      GO TO 6
C
C     (3) PREDICTING HT5 FROM FAY-RIDDELL WITH MUT5 FROM YOS
C
16    IF (TT5.LE.1500.) GO TO 17
      CALL DISCOT (TT5,PT5,TABTY,TABNUY,TAPY,11,52,4,MUT5)
      GO TO 18
17    MUT5=1.462E-6*SQRT(TT5)/(1.+112./TT5)
18    QT5FR=.760*((RHOW*MUW)**.1)*((RHOT5*MUT5)**.4)*(HT5-HW)*SQRT(BO)/(
     1(PR**0.6)*2.**(SPH/2.))
      IF (ITEST.EQ.4) GO TO 20
C
C     TOLQT REPRESENTS TOLERANCE OF ITERATION ON QT5
C
      IF (ABS(1.-QT5M/QT5FR).LE.TOLQT) GO TO 20
      IF (MM.EQ.15) GO TO 19
      MM=MM+1
      HT5=(HT5-HW)*QT5M/QT5FR+HW
      IF (SAV.EQ.1.) GO TO 25
      CALL SEARCH (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,ZSTART5,ISP,1)
      GO TO 16
25    CALL SAVE (PT5,RHOT5,HT5,ST5R,TT5,AT5,ZT5,GAMET5,3)
      GO TO 16
19    PRINT 21
      ICODE=1
```

```
20    RETURN
C
21    FORMAT (51H ITERATIONS ON HT IN SECTION 3 OF QDOT EXCEED LIMIT)
      END
      SUBROUTINE SAVE (P,RHO,H,SR,T,AM,Z,GAME,K)
C
C        SAVE OBTAINS THERMODYNAMIC PROPERTIES FOR REAL AIR
C        IS BASED ON CURVE FIT EXPRESSIONS OF AEDC-TDR-63-138
C        EXPRESSIONS OF AEDC-TDR-63-138 APPLICABLE FOR T=90 TO 15000
C
C        MAXIMUM PERCENT ERRORS- T=2000 TO 15000, AND P=1E+4 TO 1E+6
C
C                RHO      H        T        A        Z        GAME
C                2.42     1.96     2.24     2.78     0.75     5.68
C
C        INPUTS ARE PRESSURE(N/SQ METER) AND-
C                (1) ENTROPY,S/R   (K=1)
C                (2) DENSITY, KG/CUBIC METER   (K=2)
C                (3) ENTHALPY, SQ METER/SQ SEC   (K=3)
C
C        ALSO, INPUTS DENSITY AND ENTHALPY ARE INCLUDED   (K=4)
C
      DIMENSION TABSR(6), TABR(6), TABH(6)
      DIMENSION TABPM(13), TABHM(13), TABSRM(13), PM(13)
      NN=0
      MM=0
      IF (K.NE.4) GO TO 3
      CON5=.03
      DO 2 J=1,13
      PM(J)=RHO*H*CON5
      TABPM(J)=PM(J)
      P=PM(J)
      GO TO 3
1     TABHM(J)=HA
      TABSRM(J)=SR
      CON5=CON5+.03
      MM=0
      NN=0
2     CONTINUE
      CALL FTLUP (H,P,2,13,TABHM,TABPM)
      CALL FTLUP (H,SR,2,13,TABHM,TABSRM)
      MM=3
3     PLOG=ALOG10(P/1.01325E+5)
      A=PLOG*PLOG
```

```
      C=A*PLOG
      IF (K.EQ.1) GO TO 5
      IF (K.EQ.4.AND.MM.EQ.3) GO TO 5
      SRUP=142.
      SRLOW=14.
      SR=(SRUP-SRLOW)/2.+14.
    4 DELSR=(SRUP-SRLOW)/2.
      IF (NN.EQ.0) GO TO 5
      SR=SRUP-DELSR
    5 SRLOG=ALOG10(SR)
      B=SRLOG*SRLOG
      D=B*SRLOG
      X15=-39.1442+83.0558*SRLOG-38.2842*SRLOG*SRLOG
      X151=-10.*(PLOG-X15)
      IF (X151-40.) 7,6,6
    6 T15=0.0
      GO TO 10
    7 IF (X151+40.) 8,9,9
    8 T15=1.0
      GO TO 10
    9 T15=1./(1.+EXP(X151))
   10 IF (K.EQ.3.AND.MM.NE.2) GO TO 36
      IF (K.EQ.2.AND.MM.EQ.2) GO TO 36
      IF (K.EQ.4.AND.MM.EQ.3) GO TO 58
      IF (K.EQ.4.AND.MM.EQ.2) GO TO 36
C
C        COMPUTING RHO AS A FUNCTION OF P AND S/R
C
   11 XR12=-16.5527+57.45*SRLOG-30.8036*B
      XR23=499.544-938.91*SRLOG+609.028*B-135.995*D
      XR34=360.507-634.538*SRLOG+389.174*B-82.4653*D
      XR45=489.628-458.5*SRLOG+106.25*B
      XR121=-10.*(PLOG-XR12)
      XR231=-10.*(PLOG-XR23)
      XR341=-10.*(PLOG-XR34)
      XR451=-10.*(PLOG-XR45)
      IF (XR121-40.) 12,15,15
   12 IF (XR121+40.) 13,14,14
   13 TR12=1.0
      GO TO 16
   14 TR12=1./(1.+EXP(XR121))
      GO TO 16
   15 TR12=0.0
   16 IF (XR231-40.) 17,20,20
```

```
17    IF (XR231+40.) 18,19,19
18    TR23=1.0
      GO TO 21
19    TR23=1./(1.+EXP(XR231))
      GO TO 21
20    TR23=0.0
21    IF (XR341-40.) 22,25,25
22    IF (XR341+40.) 23,24,24
23    TR34=1.
      GO TO 26
24    TR34=1./(1.+EXP(XR341))
      GO TO 26
25    TR34=0.0
26    IF (XR451-40.) 27,30,30
27    IF (XR451+40.) 28,29,29
28    TR45=1.0
      GO TO 31
29    TR45=1./(1.+EXP(XR451))
      GO TO 31
30    TR45=0.0
31    RHCL1=15.951867-0.00228295*PLOG-15.994242*SRLOG+.0065187267*A+.530
     179685*PLOG*SRLOG+3.175974*B
      RHCL2=1541.1666-63.93035*PLOG-2993.1662*SRLOG+.935437*A+84.30375*S
     1RLOG*PLOG+1938.7061*B-.004746016*C-.6128404*A*SRLOG-27.422666*B*PL
     2OG-419.0881*D
      RHCL3=427.4745-18.126622*PLOG-765.47626*SRLOG+.29343169*A+22.92687
     17*PLOG*SRLOG+456.717*B-.0017033404*C-.18068309*A*SRLOG-6.9143617*B
     2*PLOG-91.131851*D
      RHCL4=206.23144-8.2270278*PLOG-329.5465*SRLOG+.1324191*A+9.8884165
     1*PLOG*SRLOG+175.03931*B-.0010178454*C-.07654371*A*SRLOG-2.6920144*
     2B*PLOG-31.237834*D
      RHCL5=-399.52358+12.809477*PLOG+411.64144*SRLOG-.097694919*A-6.220
     14477*PLOG*SRLOG-106.6733*B
      RHCAL=RHCL1+(RHCL2-RHCL1)*TR12+(RHCL3-RHCL2)*TR23+(RHCL4-RHCL3)*TR
     134+(RHCL5-RHCL4)*TR45
      RH15=-79.282533+6.3537078*PLOG+179.22721*SRLOG-.12607098*A-8.40131
     122*PLOG*SRLOG-129.95269*B+.0010037437*C+.094185511*A*SRLOG+3.12569
     266*PLOG*B+30.203862*D
      RHCAL=RH15+(RHCAL-RH15)*T15
      RHOA=(10.**RHCAL)*1.29233
      IF (K.EQ.1) GO TO 36
      IF (K.EQ.3) GO TO 58
      IF (K.EQ.2.AND.MM.EQ.1) GO TO 56
      IF (K.EQ.4.AND.MM.EQ.1) GO TO 56
```

```
C
C         CONVERGENCE TEST FOR K=2
C
          IF (ABS(1.-RHO/RHOA).LE..001) GO TO 36
          NN=NN+1
          IF (RHO.GT.RHOA) GO TO 34
 32       SRLOW=SR
          SRUP=SR+DELSR
          IF (DELSR.GT.1.) GO TO 4
          TABSR(1)=SRLOW
          TABSR(6)=SRUP
          IF (K.EQ.2.OR.K.EQ.4) GO TO 33
          N=2
          GO TO 49
 33       N=-2
          GO TO 54
 34       SRUP=SR
          SRLOW=SR-DELSR
          IF (DELSR.GT.1.) GO TO 4
          TABSR(1)=SRUP
          TABSR(6)=SRLOW
          IF (K.EQ.2.OR.K.EQ.4) GO TO 35
          N=-2
          GO TO 49
 35       N=2
          GO TO 54
C
C         COMPUTING ENTHALPY AS A FUNCTION OF P AND S/R
C
 36       IF (SRLOG-1.6) 37,37,38
 37       HRCAL=12.693869+5.3975312*PLOG-48.729217*SRLOG-.14961521*A-5.87887
         174*PLOG*SRLOG+48.19278*B+.00090144132*C+.091151473*A*SRLOG+1.62828
         229*PLOG*B-13.065267*D
          GO TO 48
 38       IF (SRLOG-1.76) 39,39,45
 39       HR22=-156.37194+6.6959228*PLOG+269.93097*SRLOG-.097179965*A-7.5379
         1714*PLOG*SRLOG-152.13866*B+.00057029937*C+.058364795*A*SRLOG+2.159
         22755*PLOG*B+28.940926*D
          HR21=-84.008522+2.5761318*PLOG+107.06198*SRLOG-.014352904*A-1.5313
         1194*PLOG*SRLOG-32.316439*B
          XH=-61.2053+114.103*SRLOG-47.5532*B
          XH1=-10.*(PLOG-XH)
          IF (XH1-40.) 40,43,43
 40       IF (XH1+40.) 41,42,42
```

```
   41    TH=1.
         GO TO 44
   42    TH=1./(1.+EXP(XH1))
         GO TO 44
   43    TH=0.0
   44    HRCAL=HR21+(HR22-HR21)*TH
         GO TO 48
   45    IF (SRLOG-1.92) 46,46,47
   46    HRCAL=-35.160671+.5366924*PLOG+56.99585*SRLOG-.022661358*A-.484703
        105*SRLOG*PLOG-27.641087*B+.00058568839*C+.016299962*A*SRLOG+.14073
        2606*B*PLOG+4.712261*D
         GO TO 48
   47    HRCAL=-114.94796+4.004583*PLOG+180.08427*SRLOG-.041327787*A-4.0366
        1535*PLOG*SRLOG-90.76006*B+.00040320694*C+.024360248*A*SRLOG+1.0462
        2299*PLOG*B+15.467804*D
   48    HR15=28.160664-2.2339873*PLOG-59.053694*SRLOG+.054973544*A+3.71832
        157*PLOG*SRLOG+40.986503*B-.0004292698*C-.040726332*A*SRLOG-1.37045
        205*PLOG*B-8.253645*D
         HRCAL=HR15+(HRCAL-HR15)*T15
         HA=(10.**HRCAL)*287.0388
         IF (K.EQ.1.OR.K.EQ.2) GO TO 58
         IF (K.EQ.3.AND.MM.EQ.1) GO TO 52
         IF (K.EQ.4) GO TO 1
C
C           CONVERGENCE TEST FOR K=3
C
         IF (ABS(1.-H/HA).LE..001) GO TO 11
         NN=NN+1
         IF (HA.GT.H) GO TO 34
         GO TO 32
C
C           INTERPOLATION FOR DELSR LESS THAN 1
C
   49    TABH(1)=HA
   50    DELSR=(TABSR(6)-TABSR(1))/5.
         DO 51 I=2,5
         TABSR(I)=TABSR(I-1)+DELSR
   51    CONTINUE
         IF (K.EQ.2.OR.K.EQ.4) GO TO 55
         DO 53 I=2,6
         MM=1
         SR=TABSR(I)
         GO TO 5
   52    TABH(I)=HA
```

```
53    CONTINUE
      CALL FTLUP (H,SR,N,6,TABH,TABSR)
      MM=2
      GO TO 5
54    TABR(1)=RHOA
      GO TO 50
55    DO 57 I=2,6
      MM=1
      SR=TABSR(I)
      GO TO 5
56    TABR(I)=RHOA
57    CONTINUE
      CALL FTLUP (RHO,SR,N,6,TABR,TABSR)
      MM=2
      GO TO 5
C
C         COMPUTING Z
C
58    XZ12=62.91-41.5*SRLOG
      XZ23=72.945-45.75*SRLOG
      XZ34=65.75-37.5*SRLOG
      XZ45=62.92-32.0*SRLOG
      XZ121=-10.*(PLOG-XZ12)
      XZ231=-10.*(PLOG-XZ23)
      XZ341=-10.*(PLOG-XZ34)
      XZ451=-10.*(PLOG-XZ45)
      ZCAL2=519.80374-23.753514*PLOG-983.90729*SRLOG+.37296957*A+30.0843
     179*PLOG*SRLOG+620.04168*B-.0021648826*C-.23710079*A*SRLOG-9.496903
     2*PLOG*B-129.78921*D
      ZCAL3=366.40674-15.517444*PLOG-647.42436*SRLOG+.18701758*A+18.0403
     183*PLOG*SRLOG+379.59834*B-.00087958438*C-.10580129*A*SRLOG-5.18882
     254*PLOG*B-73.504269*D
      ZCAL4=516.07331-16.59277*PLOG-808.49823*SRLOG+.071256235*A+16.5268
     113*PLOG*SRLOG+418.45341*B+.00094183347*C-.019727817*A*SRLOG-3.9948
     2906*PLOG*B-71.038921*D
      IF (XZ121-40.) 59,62,62
59    IF (XZ121+40.) 60,61,61
60    TZ12=1.
      GO TO 63
61    TZ12=1./(1.+EXP(XZ121))
      GO TO 63
62    TZ12=0.0
63    IF (XZ231-40.) 64,67,67
64    IF (XZ231+40.) 65,66,66
```

```
65    TZ23=1.
      GO TO 68
66    TZ23=1./(1.+EXP(XZ231))
      GO TO 68
67    TZ23=0.0
68    IF (XZ341-40.) 69,72,72
69    IF (XZ341+40.) 70,71,71
70    TZ34=1.
      GO TO 73
71    TZ34=1./(1.+EXP(XZ341))
      GO TO 73
72    TZ34=0.0
73    IF (XZ451-40.) 74,77,77
74    IF (XZ451+40.) 75,76,76
75    TZ45=1.
      GO TO 78
76    TZ45=1./(1.+EXP(XZ451))
      GO TO 78
77    TZ45=0.0
78    ZCAL=1.0+(ZCAL2-1.)*TZ12+(ZCAL3-ZCAL2)*TZ23+(ZCAL4-ZCAL3)*TZ34+(4.
     10-ZCAL4)*TZ45
      ZCAL=1.+(ZCAL-1.)*T15
      Z=ZCAL
C
C        COMPUTING T(DEG K)
C
      WO=28.967
      RUN1V=8314.34
      IF (K.EQ.2.OR.K.EQ.4) GO TO 79
      RHO=RHOA
79    T=P*WO/(RHO*RUN1V*Z)
C
C        COMPUTING A(M/SEC)
C
      IF (T-2100.) 80,80,83
80    IF (T-1500.) 82,82,81
81    IF (PLOG+1.) 83,83,82
82    CON1=SQRT(T/273.15)
      AOAO=-.0753808+CON1*(1.12644-.0552696*CON1)
      AM=331.3115*AOAO
      GO TO 104
83    XA12=635.054-1220.46*SRLOG+803.882*B-180.845*D
      XA23=373.702-663.358*SRLOG+408.854*B-86.8056*D
      XA34=1703.78-2602.97*SRLOG+1337.93*B-231.422*D
```

```
      XA22=1043.37-1820.34*SRLOG+1076.36*B-215.445*D
      XA121=-10.*(PLOG-XA12)
      XA231=-10.*(PLOG-XA23)
      XA341=-10.*(PLOG-XA34)
      XA221=-10.*(PLOG-XA22)
      A1=-4409.6241+196.82259*PLOG+8746.4634*SRLOG-3.1650299*A-262.32947
     1*PLOG*SRLOG-5786.449*B+.020004186*C+2.1429825*A*SRLOG+87.589029*PL
     2OG*B+1277.6718*D
      A21=-1814.5117+86.096078*PLOG+3315.6099*SRLOG-1.7593034*A-107.2534
     1*PLOG*SRLOG-2023.201*B+.016287679*C+1.1398134*A*SRLOG+33.659607*PL
     2OG*B+413.41945*D
      A22=2651.2944-81.405596*PLOG-3099.0064*SRLOG+.69752668*A+48.062596
     1*PLOG*SRLOG+907.70889*B
      IF (XA221-40.) 85,84,84
   84 TA22=0.0
      GO TO 88
   85 IF (XA221+40.) 86,86,87
   86 TA22=1.0
      GO TO 88
   87 TA22=1./(1.+EXP(XA221))
   88 A2=A21+(A22-A21)*TA22
      A3=-3217.8037+195.34964*PLOG+5348.2143*SRLOG-4.6268475*A-221.12705
     1*PLOG*SRLOG-2970.8649*B+.044614358*C+2.7079177*A*SRLOG+63.042803*P
     2LOG*B+553.12007*D
      A4=16976.939-476.10242*PLOG-17445.315*SRLOG+3.6534057*A+246.41125*
     1PLOG*SRLOG+4486.3118*B
      IF (XA121-40.) 90,89,89
   89 TA12=0.0
      GO TO 93
   90 IF (XA121+40.) 91,91,92
   91 TA12=1.0
      GO TO 93
   92 TA12=1./(1.+EXP(XA121))
   93 IF (XA231-40.) 95,94,94
   94 TA23=0.0
      GO TO 98
   95 IF (XA231+40.) 96,96,97
   96 TA23=1.0
      GO TO 98
   97 TA23=1./(1.+EXP(XA231))
   98 IF (XA341-40.) 100,99,99
   99 TA34=0.0
      GO TO 103
  100 IF (XA341+40.) 101,101,102
```

```
 101     TA34=1.0
         GO TO 103
 102     TA34=1./(1.+EXP(XA34))
 103     AOAO=A1+(A2-A1)*TA12+(A3-A2)*TA23+(A4-A3)*TA34
         AM=331.3115*AOAO
C
C           COMPUTING GAMF
C
 104     GAME=WO*AM**2/(RUNIV*Z*T)
         IF (K.EQ.2) GO TO 105
         IF (K.EQ.3.OR.K.EQ.4) GO TO 106
         H=HA
         GO TO 106
 105     H=HA
 106     RETURN
         END
         SUBROUTINE SEARCH (P,RHO,H1,SOR,T1,A1,Z1,GAM,ZS,ISP,K)
C
C        K=1 CORRESPONDS TO INPUTS P AND H1
C        K=2 CORRESPONDS TO INPUTS P AND RHO
C        K=3 CORRESPONDS TO INPUTS RHO AND H1
C
         DIMENSION G(4), Y1(4), Y2(4), Y3(4), Y4(4), Y5(4), Y6(4), Y7(4)
         DIMENSION ICOUNT(25), JFLAG(25), Y(9,150), P(25), RHO(25)
         DIMENSION SAVEH(25,4), SAVER(25,4), SAVET(25,4), SAVEA(25,4)
         DIMENSION SAVEZ(25,4), SAVES(25,4), SAVEG(25,4), SAVEZS(25,4)
         DIMENSION SAVEP(25,4)
         DIMENSION H1(25), T1(25), A1(25), Z1(25), SOR(25), GAM(25), ZS(25)
         DIMENSION TABT(150), TABR(150), TABP(150), TABH(150)
         DIMENSION TABA(150), TABZ(150), TABG(150), TABZS(150)
         DO 1 I=1,ISP
         ICOUNT(I)=1
         JFLAG(I)=0
 1       CONTINUE
         JUMP=0
         IT=8
         REWIND IT
 2       READ (IT) X,NV,((Y(I,L),I=1,9),L=1,NV)
         IF (ENDFILE IT) 3,9
 3       CONTINUE
         WRITE (6,40)
         DO 8 I=1,ISP
         IF (JFLAG(I).EQ.0) GO TO 4
         GO TO 8
```

```
    4   CONTINUE
        IF (K.EQ.1) GO TO 5
        IF (K.EQ.2) GO TO 6
        P(I)=0.
        GO TO 7
    5   RHO(I)=0.
        GO TO 7
    6   H1(I)=0.
    7   T1(I)=0.
        A1(I)=0.
        Z1(I)=0.
        SOR(I)=0.
        GAM(I)=0.
        ZS(I)=0.
    8   CONTINUE
        GO TO 39
    9   CONTINUE
        DO 38 J=1,ISP
        IF (JFLAG(J).EQ.' ') GO TO 38
        NN=ICOUNT(J)
        IF (K.EQ.1) GO TO 10
        IF (K.EQ.2) GO TO 11
        HH=ALOG10(H1(J)/287.0245)
        RR=ALOG10(RHO(J)/1.291489)
        GO TO 13
   10   PP=ALOG10(P(J)/1.01325E+5)
        HH=ALOG10(H1(J)/287.0245)
        GO TO 12
   11   PP=ALOG10(P(J)/1.01325E+5)
        RR=ALOG10(RHO(J)/1.291489)
   12   IF ((PP-Y(3,1))*(PP-Y(3,NV)).LT.0.) GO TO 15
        GO TO 14
   13   IF ((RR-Y(2,1))*(RR-Y(2,NV)).LT.0.) GO TO 15
   14   SAVEP(J,1)=0.
        SAVEH(J,1)=0.
        SAVER(J,1)=0.
        SAVET(J,1)=0.
        SAVEA(J,1)=0.
        SAVEZ(J,1)=0.
        SAVES(J,1)=0.
        SAVEG(J,1)=0.
        SAVEZS(J,1)=0.
        NN=2
        GO TO 24
```

```
15    DO 16 I=1,NV
      TABT(I)=Y(1,I)
      TABR(I)=Y(2,I)
      TABP(I)=Y(3,I)
      TABH(I)=Y(4,I)
      TABG(I)=Y(5,I)
      TABA(I)=Y(6,I)
      TABZ(I)=Y(7,I)
      TABZS(I)=Y(9,I)
16    CONTINUE
      IF (K.EQ.3) GO TO 17
      CALL DISCOT (PP,PP,TABP,TABH,TABH,-130,NV,0,ANS1)
      CALL DISCOT (PP,PP,TABP,TABR,TABR,-130,NV,0,ANS2)
      CALL DISCOT (PP,PP,TABP,TABT,TABT,-130,NV,0,ANS3)
      CALL DISCOT (PP,PP,TABP,TABA,TABA,-130,NV,0,ANS4)
      CALL DISCOT (PP,PP,TABP,TABZ,TABZ,-130,NV,0,ANS5)
      CALL DISCOT (PP,PP,TABP,TABG,TABG,-130,NV,0,ANS6)
      CALL DISCOT (PP,PP,TABP,TABZS,TABZS,-130,NV,0,ANS7)
      SAVES(J,NN)=X
      SAVEH(J,NN)=ANS1
      SAVER(J,NN)=ANS2
      SAVET(J,NN)=ANS3
      SAVEA(J,NN)=ANS4
      SAVEZ(J,NN)=ANS5
      SAVEG(J,NN)=ANS6
      SAVEZS(J,NN)=ANS7
      GO TO 18
17    CALL DISCOT (RR,RR,TABR,TABH,TABH,-130,NV,0,ANS1)
      CALL DISCOT (RR,RR,TABR,TABT,TABT,-130,NV,0,ANS3)
      CALL DISCOT (RR,RR,TABR,TABA,TABA,-130,NV,0,ANS4)
      CALL DISCOT (RR,RR,TABR,TABZ,TABZ,-130,NV,0,ANS5)
      CALL DISCOT (RR,RR,TABR,TABG,TABG,-130,NV,0,ANS6)
      CALL DISCOT (RR,RR,TABR,TABZS,TABZS,-130,NV,0,ANS7)
      CALL DISCOT (RR,RR,TABR,TABP,TABP,-130,NV,0,ANS8)
      SAVES(J,NN)=X
      SAVEH(J,NN)=ANS1
      SAVET(J,NN)=ANS3
      SAVEA(J,NN)=ANS4
      SAVEZ(J,NN)=ANS5
      SAVEG(J,NN)=ANS6
      SAVEZS(J,NN)=ANS7
      SAVEP(J,NN)=ANS8
18    IF (K.EQ.1) GO TO 20
      IF (K.EQ.2) GO TO 21
```

```
      IF (SAVEH(J,NN).GT.HH) GO TO 25
      IF (NN.EQ.3) GO TO 19
      NN=NN+1
      GO TO 24
 19   SAVEP(J,1)=SAVEP(J,2)
      SAVEH(J,1)=SAVEH(J,2)
      SAVET(J,1)=SAVET(J,2)
      SAVEA(J,1)=SAVEA(J,2)
      SAVEZ(J,1)=SAVEZ(J,2)
      SAVES(J,1)=SAVES(J,2)
      SAVEG(J,1)=SAVEG(J,2)
      SAVEZS(J,1)=SAVEZS(J,2)
      SAVEP(J,2)=SAVEP(J,3)
      SAVEH(J,2)=SAVEH(J,3)
      SAVET(J,2)=SAVET(J,3)
      SAVEA(J,2)=SAVEA(J,3)
      SAVEZ(J,2)=SAVEZ(J,3)
      SAVES(J,2)=SAVES(J,3)
      SAVEG(J,2)=SAVEG(J,3)
      SAVEZS(J,2)=SAVEZS(J,3)
      GO TO 24
 20   IF (SAVEH(J,NN).GT.HH) GO TO 25
      GO TO 22
 21   IF (SAVER(J,NN).LT.RR) GO TO 25
 22   IF (NN.EQ.3) GO TO 23
      NN=NN+1
      GO TO 24
 23   SAVER(J,1)=SAVER(J,2)
      SAVEH(J,1)=SAVEH(J,2)
      SAVET(J,1)=SAVET(J,2)
      SAVEA(J,1)=SAVEA(J,2)
      SAVEZ(J,1)=SAVEZ(J,2)
      SAVES(J,1)=SAVES(J,2)
      SAVEG(J,1)=SAVEG(J,2)
      SAVEZS(J,1)=SAVEZS(J,2)
      SAVER(J,2)=SAVER(J,3)
      SAVEH(J,2)=SAVEH(J,3)
      SAVET(J,2)=SAVET(J,3)
      SAVEA(J,2)=SAVEA(J,3)
      SAVEZ(J,2)=SAVEZ(J,3)
      SAVES(J,2)=SAVES(J,3)
      SAVEG(J,2)=SAVEG(J,3)
      SAVEZS(J,2)=SAVEZS(J,3)
 24   ICOUNT(J)=NN
```

```
      GO TO 38
25    IF (NN.EQ.4) GO TO 26
      NN=NN+1
      ICOUNT(J)=NN
      GO TO 38
26    JFLAG(J)=1
      DO 30 M=1,4
      IF (K.EQ.1) GO TO 27
      IF (K.EQ.2) GO TO 28
      G(M)=SAVEH(J,M)
      Y1(M)=SAVEP(J,M)
      GO TO 29
27    G(M)=SAVEH(J,M)
      Y1(M)=SAVER(J,M)
      GO TO 29
28    G(M)=SAVER(J,M)
      Y1(M)=SAVEH(J,M)
29    Y2(M)=SAVFT(J,M)
      Y3(M)=SAVEA(J,M)
      Y4(M)=SAVEZ(J,M)
      Y5(M)=SAVES(J,M)
      Y6(M)=SAVEG(J,M)
      Y7(M)=SAVEZS(J,M)
30    CONTINUE
      IF (K.EQ.1) GO TO 31
      IF (K.EQ.2) GO TO 33
      CALL INTRP (4,G,Y1,HH,P)
      GO TO 32
31    CALL INTRP (4,G,Y1,HH,R)
32    CALL INTRP (4,G,Y2,HH,T)
      CALL INTRP (4,G,Y3,HH,A)
      CALL INTRP (4,G,Y4,HH,Z)
      CALL INTRP (4,G,Y5,HH,SR1)
      CALL INTRP (4,G,Y6,HH,GAM1)
      CALL INTRP (4,G,Y7,HH,ZS1)
      GO TO 34
33    CALL INTRP (4,G,Y1,RR,H)
      CALL INTRP (4,G,Y2,RR,T)
      CALL INTRP (4,G,Y3,RR,A)
      CALL INTRP (4,G,Y4,RR,Z)
      CALL INTRP (4,G,Y5,RR,SR1)
      CALL INTRP (4,G,Y6,RR,GAM1)
      CALL INTRP (4,G,Y7,RR,ZS1)
34    IF (K.EQ.1) GO TO 35
```

```
      IF (K.EQ.2) GO TO 36
      P(J)=(10.**P)*1.01325E+5
      GO TO 37
35    RHO(J)=(10.**R)*1.291489
      GO TO 37
36    H1(J)=(10.**H)*287.0245
37    T1(J)=T
      A1(J)=A*331.4184
      Z1(J)=Z
      SOR(J)=SR1
      GAM(J)=GAM1
      ZS(J)=ZS1
      JUMP=JUMP+1
      IF (JUMP.EQ.ISP) GO TO 39
38    CONTINUE
      GO TO 2
39    CONTINUE
      RETURN
C
40    FORMAT (1H1,60X,7HWARNING////)
      END
      SUBROUTINE SLOW (XX,Z,I1,J1,IT,NV,NERR,Y,X)
C     TAPE IS WRITTEN WITH LINES OF CONSTANT XX
C     Z(I1) AND XX ARE INDEPENDENT VARIABLES
C     Z(J1) IS THE DEPENDENT VARIABLE
C     AK= +1. IF XX INCREASES MONOTONICALLY ON TAPE
C     AK= -1. IF XX DECREASES MONOTONICALLY ON TAPE
C     IT= TAPE UNIT
C     NV= NO. OF VARIABLES ON TAPE FOR EACH XX .(NOT GREATER THAN 9)
C     NO. OF POINTS FOR EACH XX NOT GREATER THAN 150
C     BEGIN EXECUTION
      DIMENSION X(4), Y(4,9,150), Z(9), U(4), V(4), W(4), NP(4)
      COMMON ICOUNT,IMET(2),NP,ABAR,ME,MF
      REAL MF,ME
      ICOUNT=ICOUNT+1
      IF (IMET(1)) 3,1,3
1     BACKSPACE IT
      READ (IT) DUM
      REWIND IT
      DO 2 K=1,3
      READ (IT) X(K),J,((Y(K,I,L),I=1,NV),L=1,J)
2     NP(K)=J
      XW=X(2)-X(1)
      AK=ABS(XW)/XW
```

```
      DIR1=1.
      IMET(1)=1
      XXX=XX
      NERR=0
      IM=3
      GO TO 18
3     NERR=0
C     EXCEPT FOR FIRST TIME THROUGH
      IF ((XX-X(M1))*(XX-X(M2))) 25,25,4
4     TEMP=(XX-XXX)*AK
      DIR2=ABS(TEMP)/TEMP
      GO=DIR1*DIR2
      XXX=XX
      DIR1=DIR2
      IF (DIR2) 5,35,16
C
C     NEGATIVE DIRECTION
5     IF (GO) 6,35,7
6     BACKSPACE IT
      BACKSPACE IT
      BACKSPACE IT
      GO TO 9
7     IM=IM-1
      IF (IM) 8,8,9
8     IM=4
9     M1=IM+1
      BACKSPACE IT
      BACKSPACE IT
      IF (M1-4) 11,11,10
10    M1=1
11    M2=M1+1
      IF (M2-4) 13,13,12
12    M2=1
13    READ (IT) X(IM),J,((Y(IM,I,L),I=1,NV),L=1,J)
      NP(IM)=J
      IF ((XX-X(M1))*(XX-X(M2))) 25,25,14
14    IF (X(M1)-X(M2)) 7,15,7
C     ERROR, VARIABLE OFF FRONT END OF TAPE
15    CONTINUE
      NERR=1
      GO TO 36
C
C     POSITIVE DIRECTION
16    IF (GO) 17,35,18
```

```
17    READ (IT) DUM
      READ (IT) DUM
      READ (IT) DUM
      GO TO 20
18    IM=IM+1
      IF (IM-4) 20,20,19
19    IM=1
20    M1=IM-1
      IF (M1) 21,21,22
21    M1=4
22    M2=M1-1
      IF (M2) 23,23,24
23    M2=4
24    READ (IT) X(IM),J,((Y(IM,I,L),I=1,NV),L=1,J)
      NP(IM)=J
      IF ((XX-X(M1))*(XX-X(M2))) 25,25,18
C
C     TAPE SEARCH COMPLETE , DO CROSS FOUR POINT
25    DO 34 K=1,4
      NPK=NP(K)-1
      DO 26 I=1,NPK
      IF ((Y(K,I1,I)-Z(I1))*(Y(K,I1,I+1)-Z(I1))) 27,27,26
26    CONTINUE
      NERR=1
      GO TO 36
27    IF (I-1) 29,28,29
28    J=0
      GO TO 32
29    IF (I-NPK) 31,30,31
30    J=NPK-3
      GO TO 32
31    J=I-2
32    DO 33 L=1,4
      MX=L+J
      U(L)=Y(K,I1,MX)
33    V(L)=Y(K,J1,MX)
34    CALL INTRP (4,U,V,Z(I1),W(K))
      CALL INTRP (4,X,W,XX,Z(J1))
      RETURN
35    CONTINUE
36    NERR=1
      IF (IMET(2)) 39,37,39
37    IMET(2)=1
      WRITE (6,40) XX,I1,Z(I1),J1
```

```
      DO 38 IM=1,4
      WRITE (6,41) I1,Z(I1),X(IM)
      NXXXX=NP(IM)
38    WRITE (6,42) ((Y(IM,I,L),I=1,NV),L=1,NXXXX)
39    RETURN
C
40    FORMAT (///39H NO SOLUTION ON TAPE FOR THE CONDITIONS//5X,6H  S/R=
     1F12.6,37X,9H EVALUATE/6X,2HZ(I1,2H)=E16.8,38X,3H Z(I1,1H)///)
41    FORMAT (1H12X,3H Z(I1,2H)=F10.6/3X,5H S/R=F12.6//120H     T, DEG K
     1 LOG(RHO)     LOG(P)  LOG(H/R)     GAMMA       A/AA         Z      H
     2/RT        Z*                                  //)
42    FORMAT (2XF12.2,8F10.6)
      END
      SUBROUTINE INTRP (N,X,Y,XINT,YINT)
      DIMENSION X(N), Y(N)
      YINT=0.
      DO 3 I=1,N
      SUMN=1.
      SUMD=1.
      DO 2 J=1,N
      IF (J-I) 1,2,1
1     SUMN=SUMN*(XINT-X(J))
      SUMD=SUMD*(X(I)-X(J))
2     CONTINUE
3     YINT=YINT+Y(I)*SUMN/SUMD
      RETURN
      END
-  ,
 $INP ITEST=1,P5M=1040,PT5M=1.746E+5,U5M=6100,RUN=1,RN=.0127$
 $INP ITEST=1,P5M=1040,PT5M=1.746E+5,U5M=6100,RUN=1,RN=.0127,SAV=0$
 $INP ITEST=5,P5M=1040,RHO5M=.00485,U5M=6100,RUN=2,RN=.0127$
 $INP ITEST=5,P5M=1040,RHO5M=.00485,U5M=6100,RUN=2,RN=.0127,SAV=0$
 $INP ITEST=3,P5M=1040,PT5M=1.746E+5,QT5M=2.743E+7,RUN=3,RN=.0127$
 $INP ITEST=3,P5M=1040,PT5M=1.746E+5,QT5M=2.743E+7,RUN=3,RN=.0127,SAV=0$
-  ,
```

A sample data printout is presented on the following page. The FORTRAN symbols in the printout and the corresponding symbols defined in the section entitled "Symbols" are as follows:

P1	$(p_1)_m$
V1	$(V_1)_m$
PT	$(p_t)_m$
QT	$(\dot{q}_t)_m$
RHO1	$(\rho_1)_m$
RHOT	$(\rho_t)_m$
P	p
RHO	ρ
T	T
H	h
S/R	s/R
Z	Z
GAME	γ_E
A	a
V	V
M	M
NRE	N_{Re}
QTCO	$\dot{q}_t$ (ref. 39)
QTHOS	$\dot{q}_t$ (ref. 40)
QTFR	$\dot{q}_t$ (ref. 41)
QTPT	$\dot{q}_t$ (ref. 42)
QTDE	$\dot{q}_t$ (ref. 43)
QTZO	$\dot{q}_t$ (ref. 44)
RN	r_g

REAL-AIR DATA REDUCTION PROGRAM OF MILLER

ALL PHYSICAL QUANTITIES IN MKS UNITS- NASA SP-7012

MEASURED INPUTS

RUN	P1	V1	PT	QT	RHO1	RHOT	TIME
2.000E+00	1.040E+03	6.100E+03	0.	0.	4.850E-03	0.	1.000E-04

FREE-STREAM CONDITIONS

P	RHO	T	H	S/R	Z	GAME	A	V	M	NRE
1.040E+03	4.850E-03	7.462E+02	7.635E+05	3.177E+01	1.000E+00	1.361E+00	5.400E+02	6.100E+03	1.130E+01	8.520E+05

STATIC CONDITIONS BEHIND NORMAL SHOCK

P	RHO	T	H	S/R	Z	GAME	A	V	M	NRE
1.674E+05	6.225E-02	6.619E+03	1.926E+07	4.399E+01	1.414E+00	1.142E+00	1.752E+03	4.757E+02	2.715E-01	1.717E+05

STAGNATION CONDITIONS BEHIND NORMAL SHOCK

P	RHO	T	H	S/R	Z	GAME	A
1.746E+05	6.458E-02	6.643E+03	1.937E+07	4.399E+01	1.416E+00	1.142E+00	1.757E+03

STAGNATION POINT HEAT TRANSFER PREDICTIONS

QTCO	QTHOS	QTFR	QTPT	QTDE	QTZO	RN
2.791E+07	2.345E+07	2.867E+07	3.447E+07	2.893E+07	2.743E+07	1.270E-02

APPENDIX E

COMPUTER PROGRAM INPUTS

The FORTRAN NAMELIST capability is used for data input with INP as the NAMELIST name. The inputs necessary to utilize the computer program in appendix D are as follows:

Program symbol	Description and unit
ITEST	Identifies data reduction procedure to be used
RUN	Identifies facility test number
TØLPT	Desired tolerance of iteration involving p_t
TØLQT	Desired tolerance of iteration involving $\dot{q}_t$
TØLRHØ	Desired tolerance of iteration involving ρ_1
SPH	SPH = 0 for spherical $\dot{q}_t$ model SPH = 1 for transverse-cylinder $\dot{q}_t$ model
YØS	YØS = 0 for μ_t in $\dot{q}_t$ predictions from Hansen (ref. 46) YØS = 1 for μ_t in $\dot{q}_t$ prediction from Yos (ref. 47)
QDØ	QDØ = 0 if do not want various $\dot{q}_t$ calculated QDØ = 1 if want various $\dot{q}_t$ calculated
TWALL	TWALL = 0 for $T_w = T_{amb}$ TWALL = 1 if want to calculate T_w using equation (11)
TAU	Test time, τ, sec
ETA	Product $\rho c_p k$ of model surface material, W^2-sec/m^4-K^2
TWE	$T_{w,amb}$, K
RN	r_g, m
P5M	$(p_1)_m$, N/m^2
PT5M	$(p_t)_m$, N/m^2

Program symbol	Description and unit
U5M	$(V_1)_m$, m/sec
QT5M	$(\dot{q}_t)_m$, W/m^2
RHØ5M	$(\rho_1)_m$, kg/m^3
RHØT5M	$(\rho_t)_m$, kg/m^3
SAV	SAV = 0 for use of AEDC tape
	SAV = 1 for use of subroutine SAVE (K)

In using a specific ITEST, only the measured inputs associated with that ITEST need be included. For convenience, the required inputs corresponding to a specific ITEST are indicated in the following table:

ITEST	P5M	PT5M	U5M	QT5M	RHO5M	RHOT5M
1	X	X	X			
2		X	X	X		
3	X	X		X		
4	X		X	X		
5	X		X		X	
6	X	X			X	
7		X			X	X
8	X	X				X
9		X	X			X

To reduce the number of inputs in INP, values are assigned (within the computer program) to several input quantities; hence, these quantities may be excluded from INP, unless a change in the quantity from the assigned value is desired. The assigned values are as follows:

Program symbol	Assigned value
TØLPT	0.001
TØLQT	0.005
TØLRHØ	0.001
SPH	0
YØS	1
QDØ	1
TWALL	0
TAU	1×10^{-4}
ETA	2.045×10^{8}
TWE	300
RN	0.01
SAV	1

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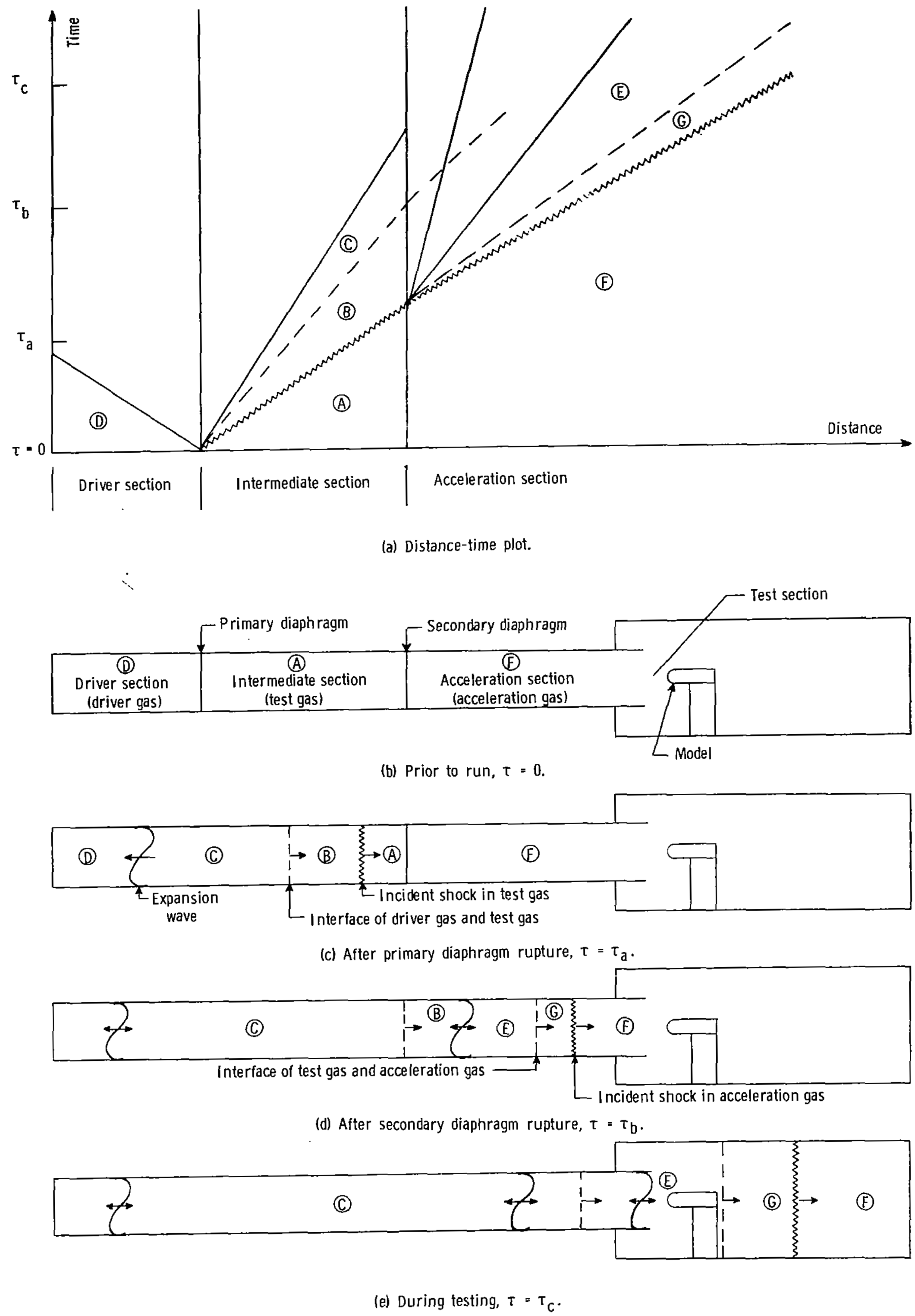


Figure 1.- Sketches illustrating expansion-tube cycle. Region E denotes free-stream conditions (i.e., test region).

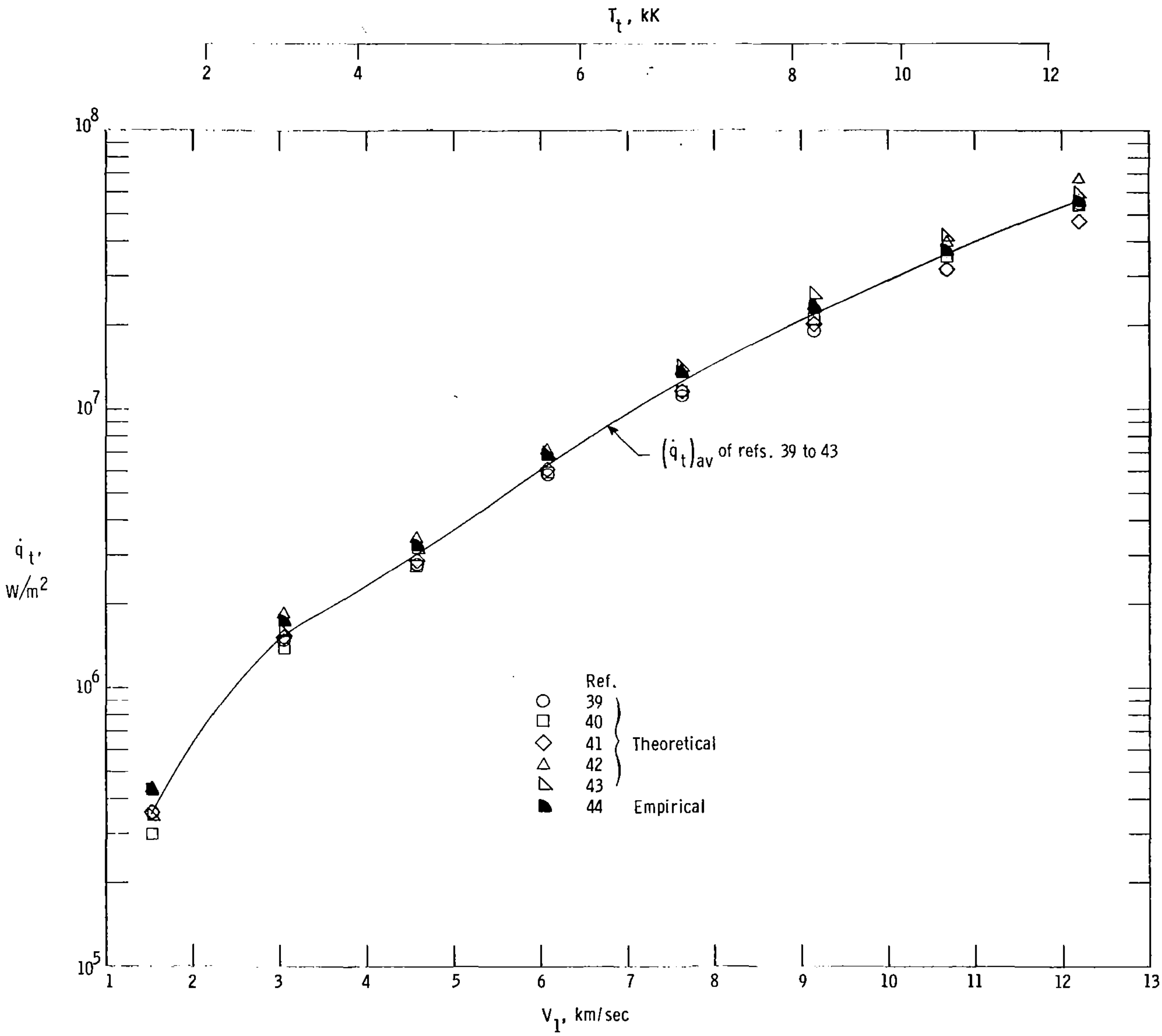
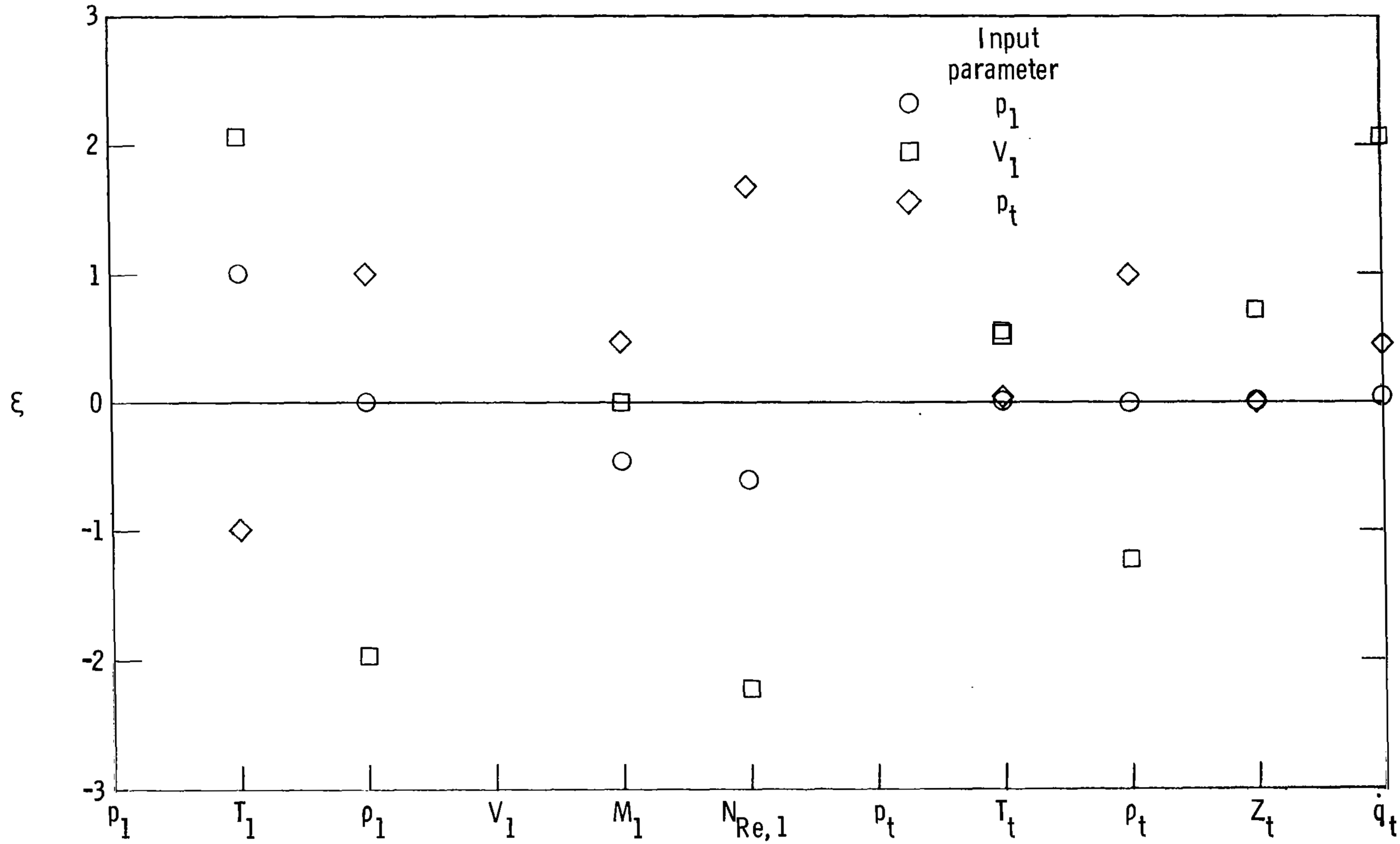
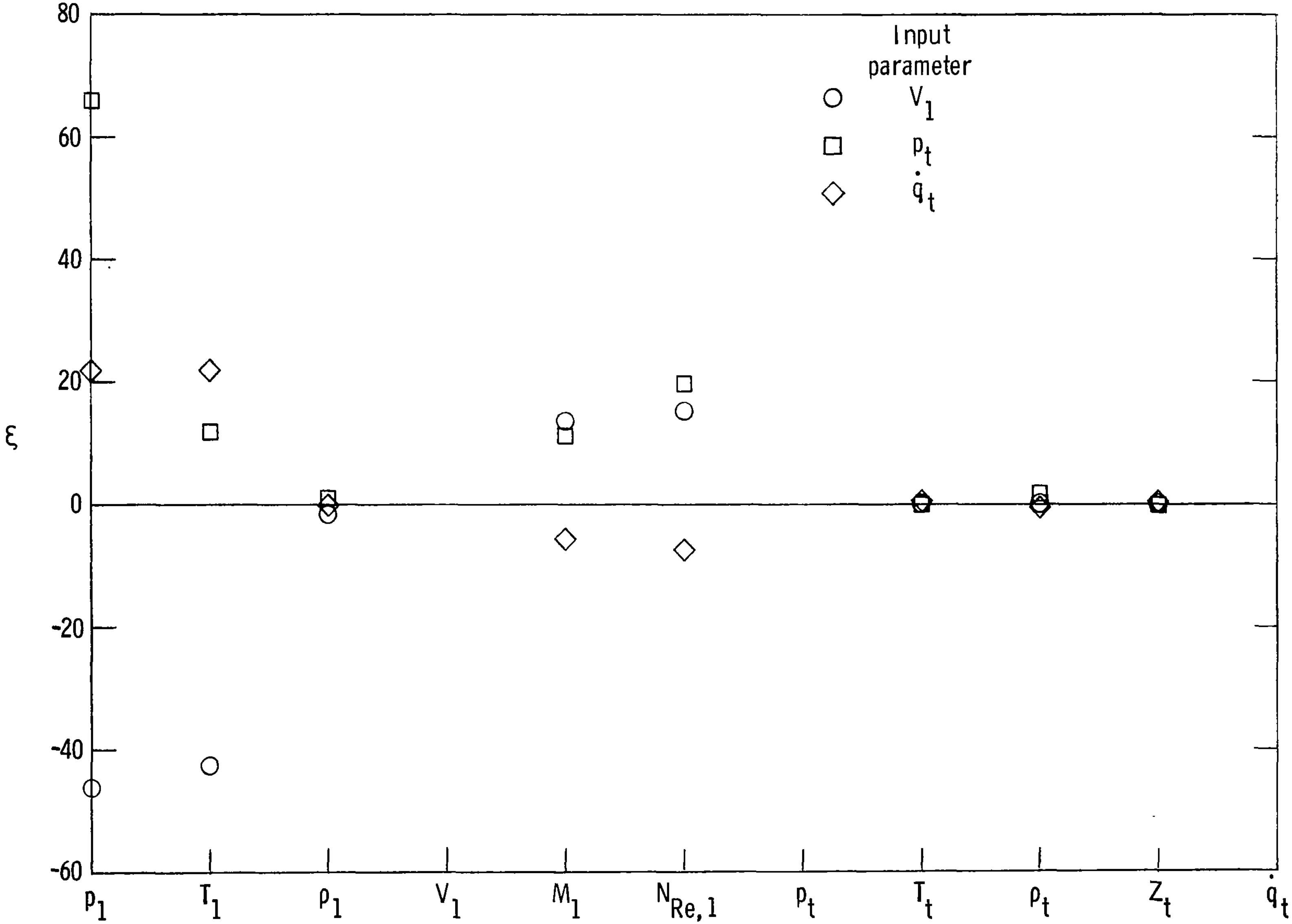


Figure 2.- Comparison of several methods for predicting stagnation-point heat-transfer rate in air. r_g = 1.27 cm (sphere); T_w = 300 K.



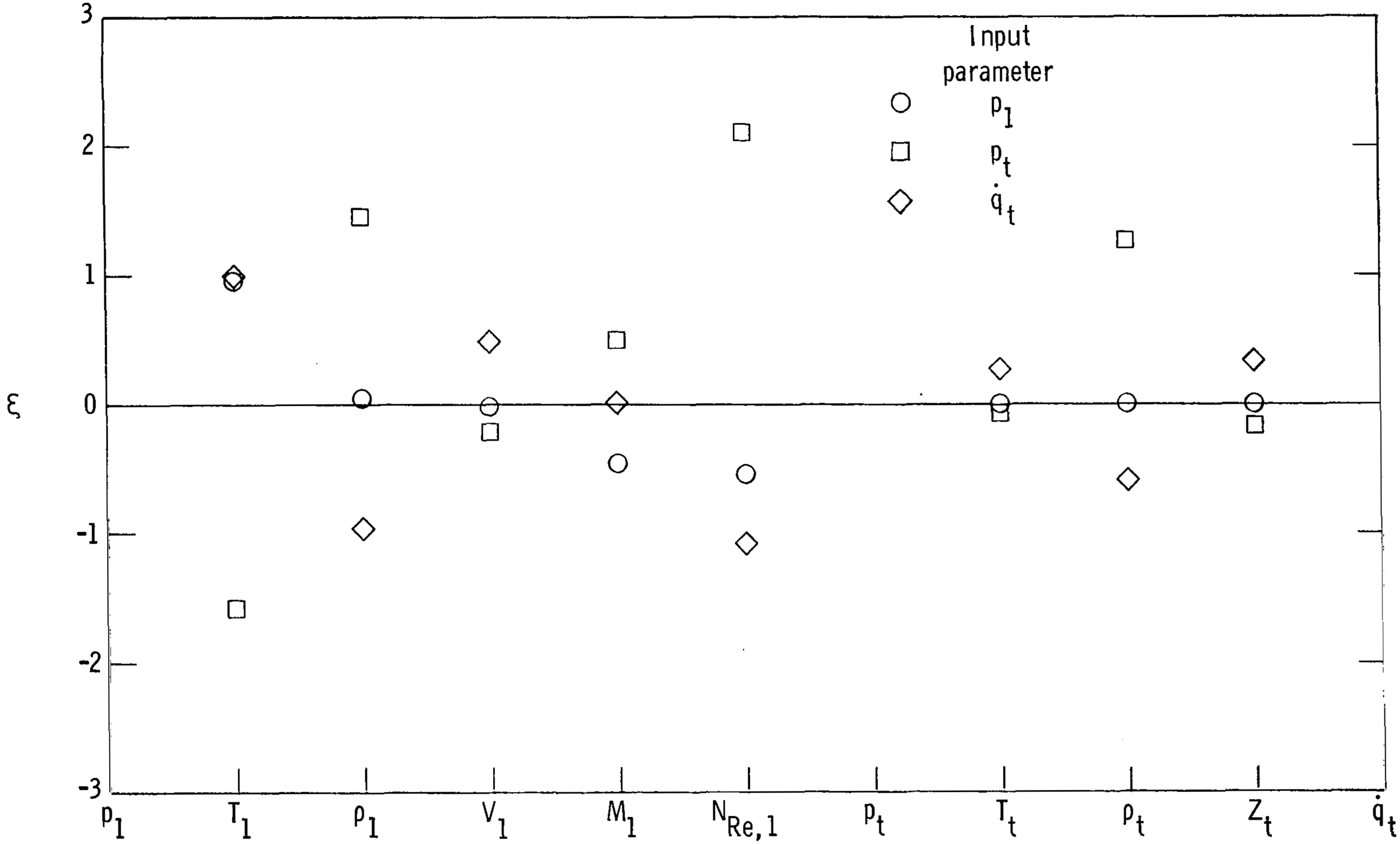
(a) ITEST = 1.

Figure 3.- Variation of error parameter ξ for free-stream and stagnation-point flow quantities.



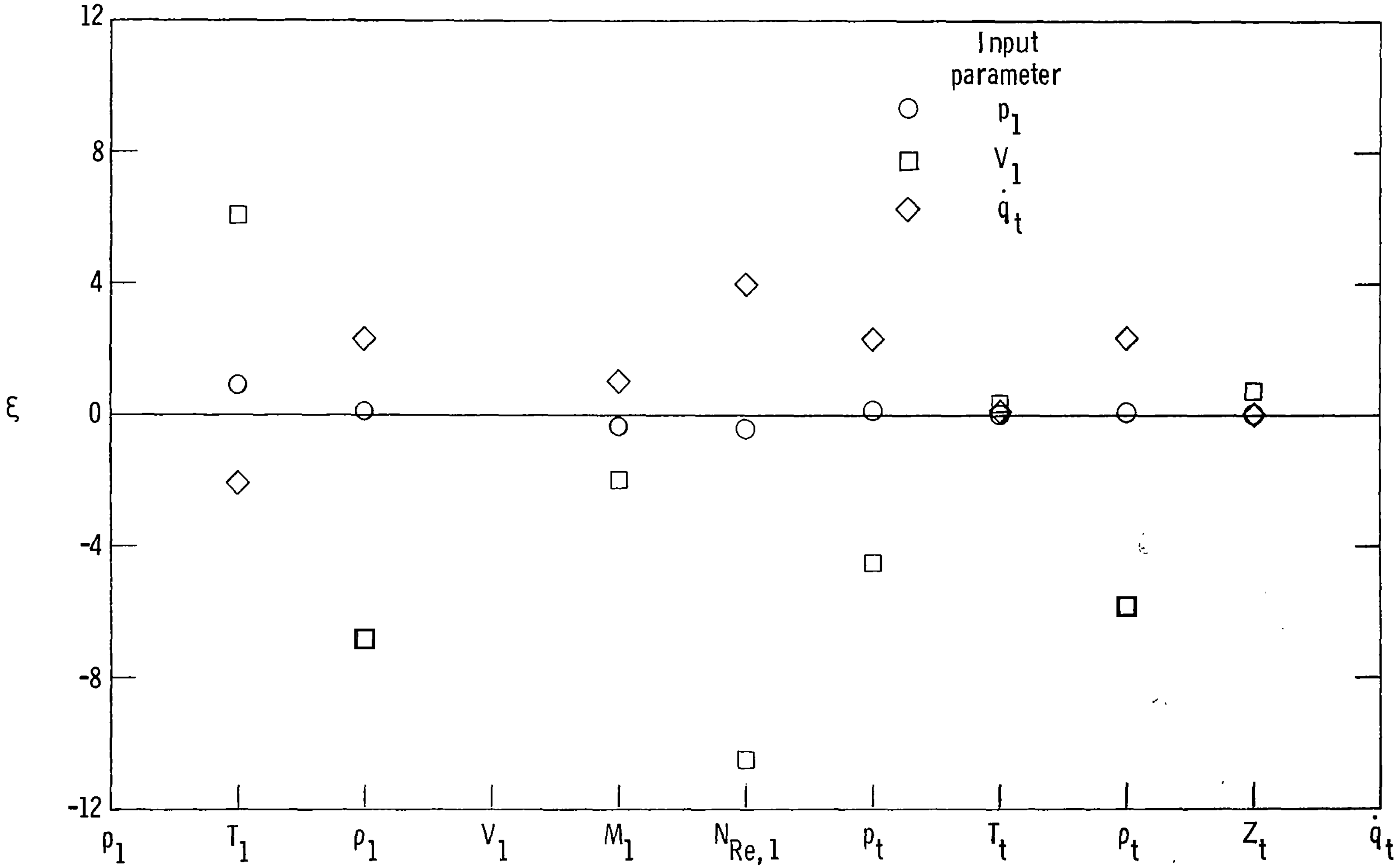
(b) ITEST = 2.

Figure 3.- Continued.



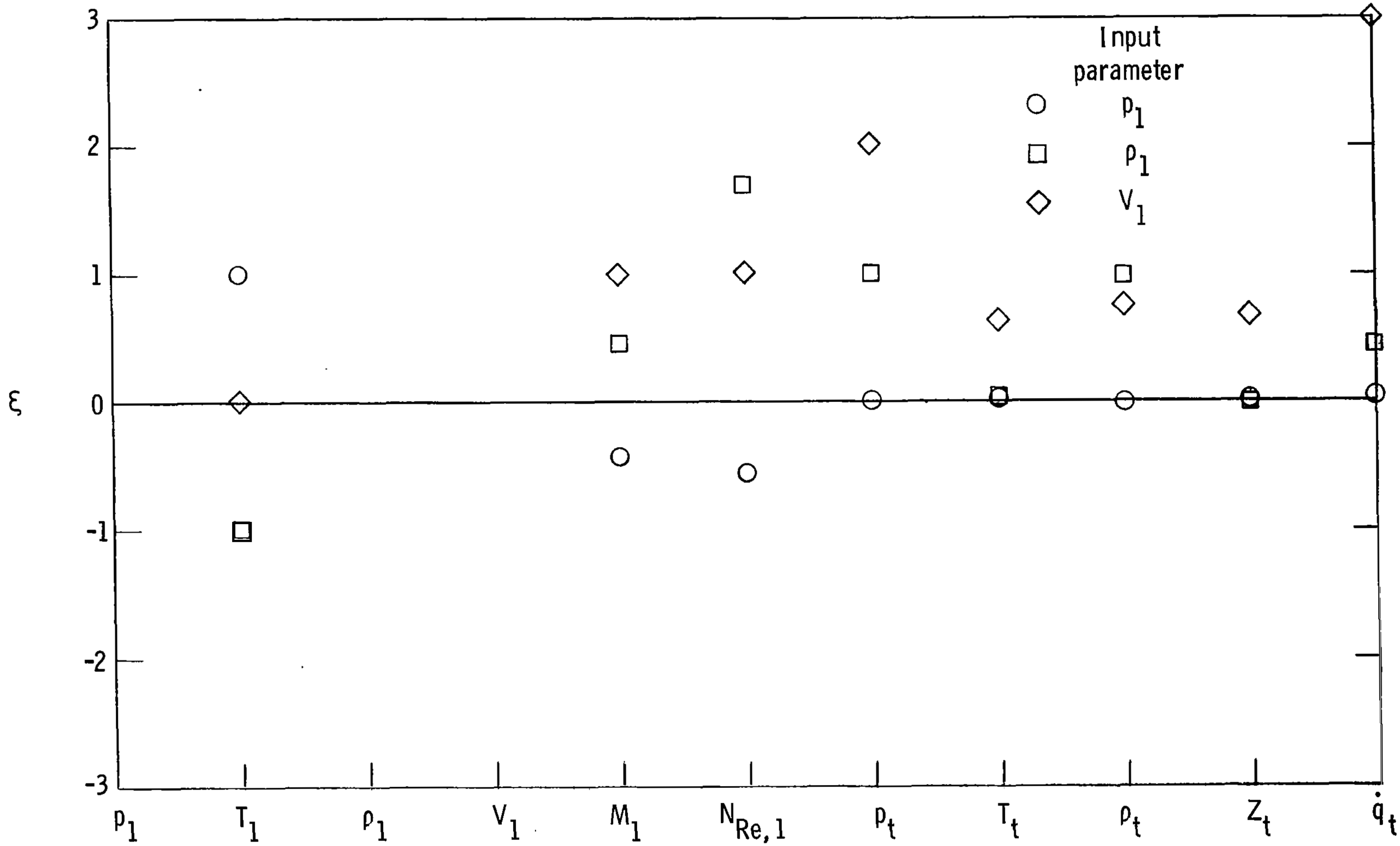
(c) ITEST = 3.

Figure 3.- Continued.



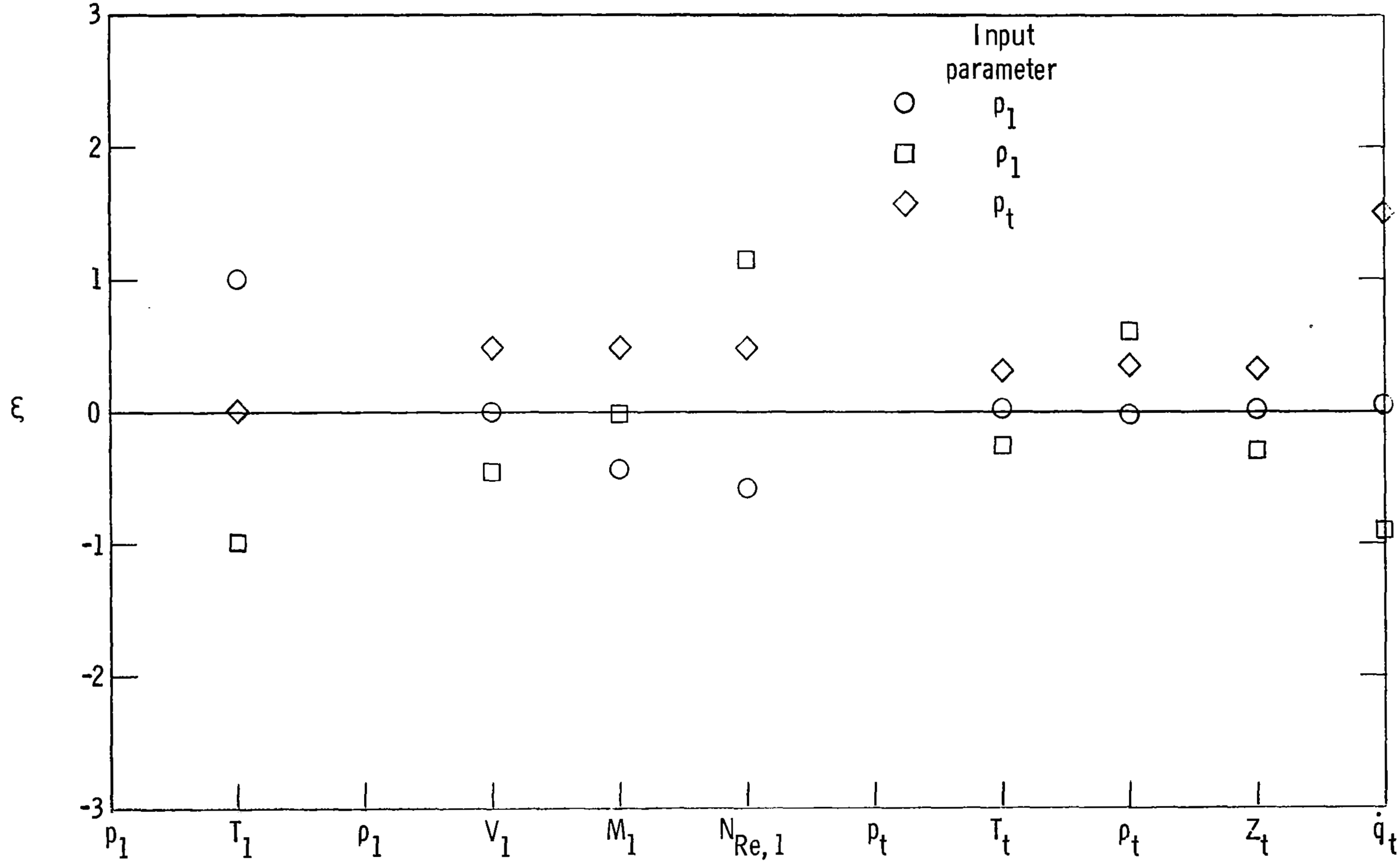
(d) ITEST = 4.

Figure 3.- Continued.



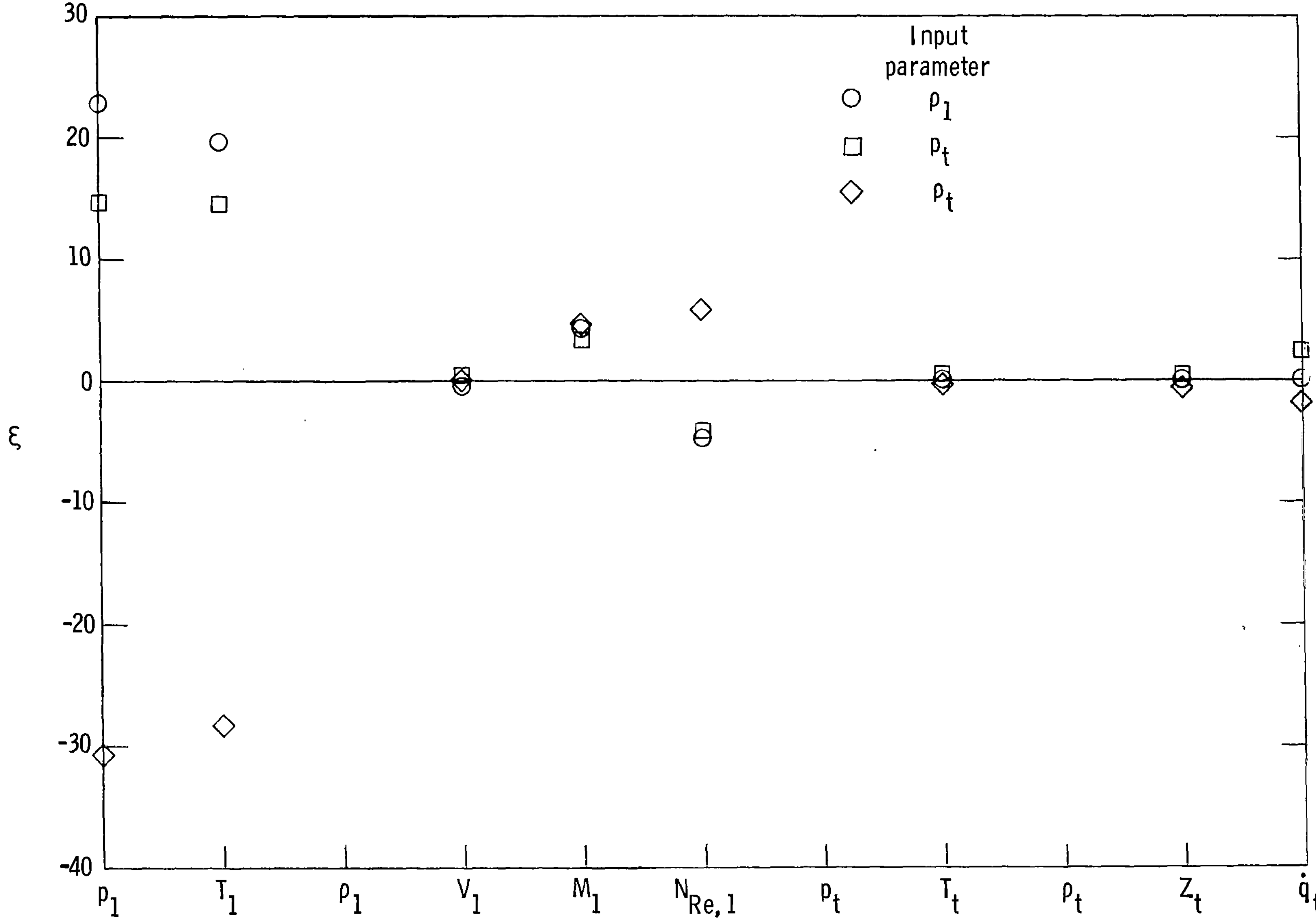
(e) ITEST = 5.

Figure 3.- Continued.



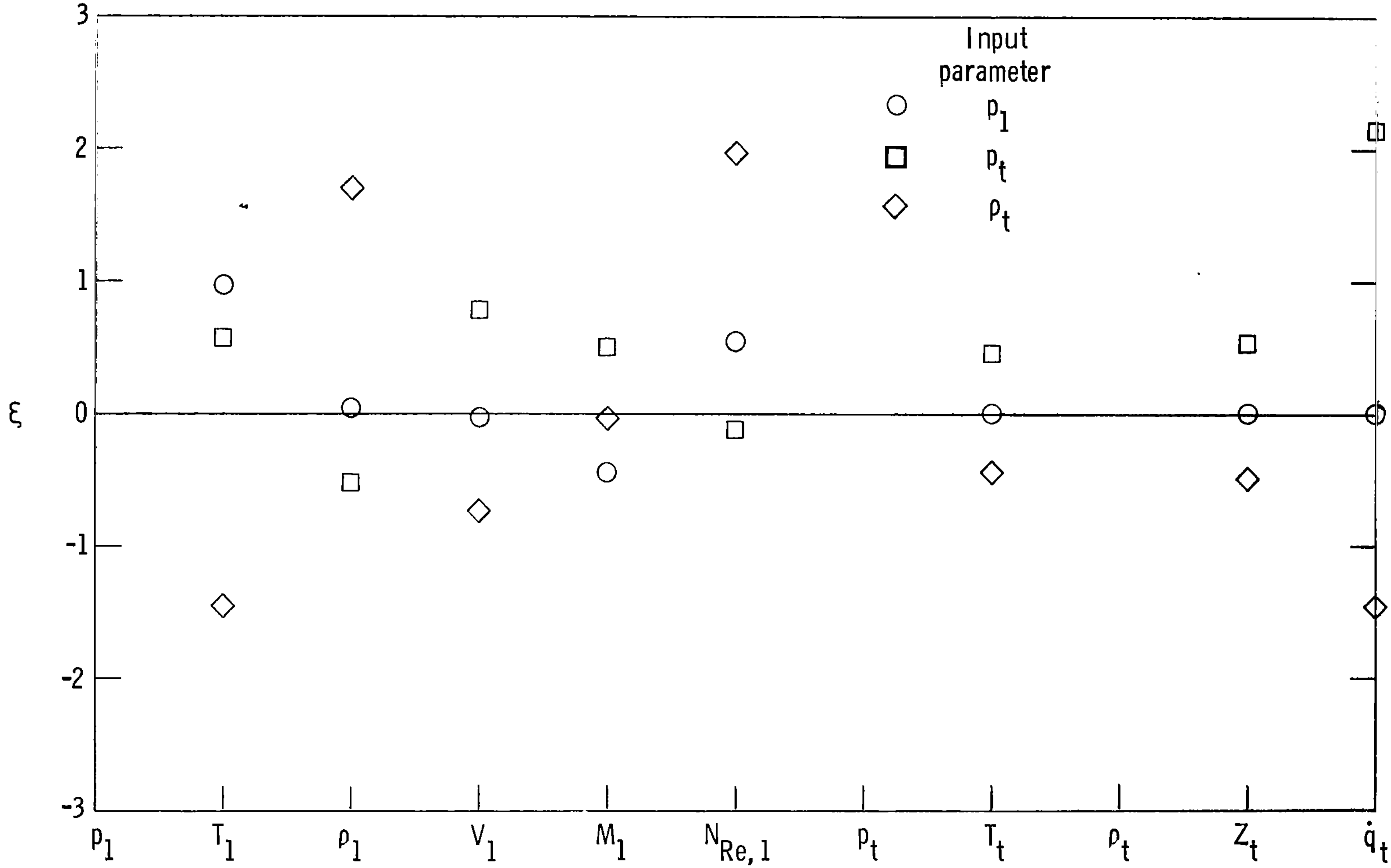
(f) ITEST = 6.

Figure 3.- Continued.



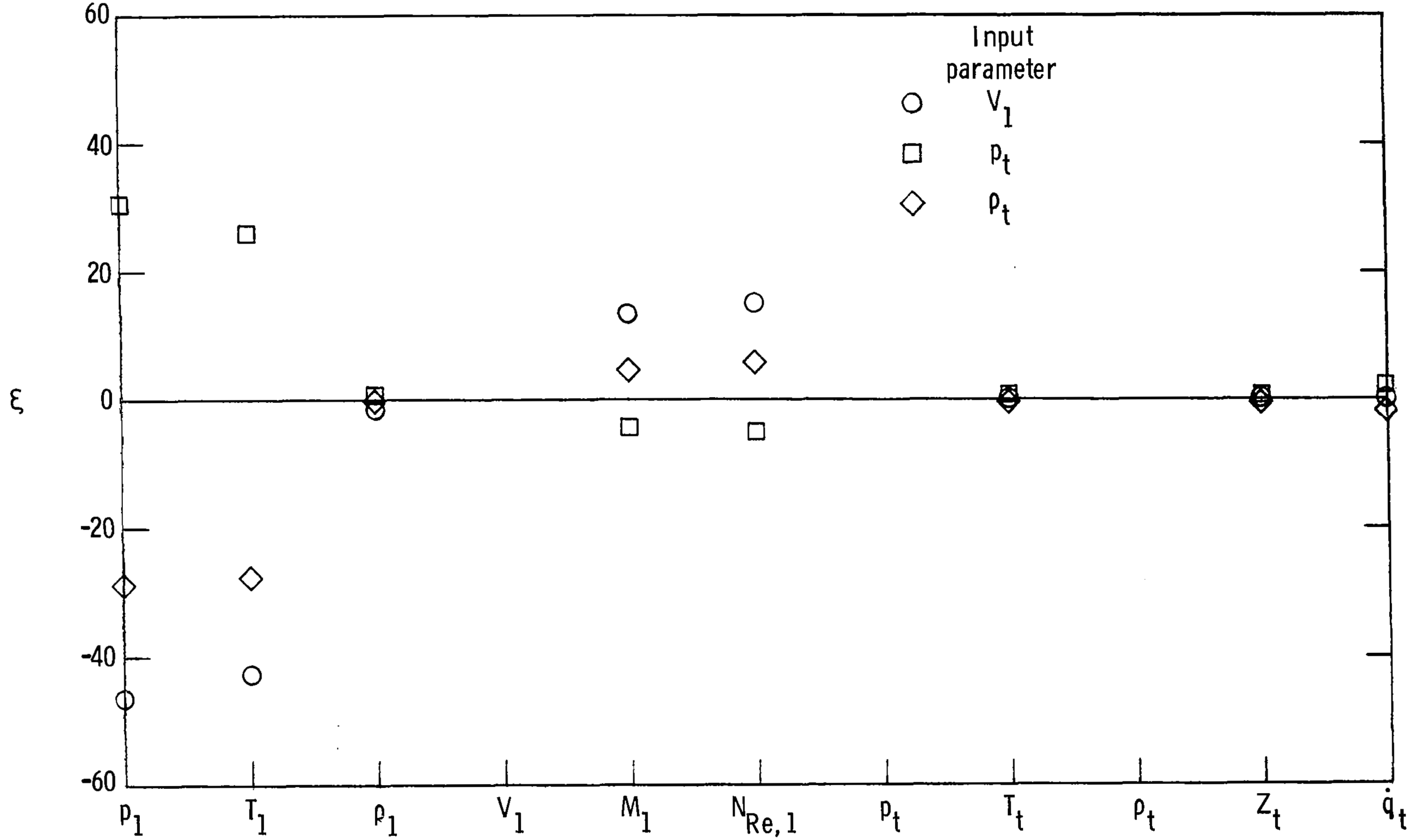
(g) ITEST = 7.

Figure 3.- Continued.



(h) ITEST = 8.

Figure 3.- Continued.



(i) ITEST = 9.

Figure 3.- Concluded.

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